Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

92-06196/

INFO-0420

EFFECTS OF MICRODISTRIBUTION OF TRITIUM ON DOSE CALCULATIONS

(AECB Project No. 3.167.1)

by

W.V. Prestwich, C.S. Kwok
and J. Nunes

A research report prepared for
the Atomic Energy Control Board
Ottawa, Canada

June 1992

Canada

Research report

EFFECTS OF MICRODISTRIBUTION OF TRITIUM ON DOSE CALCULATIONS

Prepared by C.S. Kwok, W.Y. Prestwich and J. Nunes under contract to the Atomic Energy Control Board.

ABSTRACT

Literature and data pertaining to the microdosimetry, relative biological effectiveness, subcellular distribution, organ uptake and retention for organically-bound tritium are reviewed.

The quality factor for the electron degradation spectrum associated with the radiation field of tritium β-rays in water was calculated. The value was found to be 1.9 ± .2. A related experimental measure of quality with value 1.6 ± .2 and an estimate of 1.3 based on simulation studies are cited.

The average value for relative biological effectiveness for a data base of 55 values was found to be 1.8 ± .1. The influence of reference radiation, in vivo versus in vitro methodologies, and the use of tritiated thymidine or tritiated water are discussed.

A methodology designed to estimate the effects of subcellular distribution is described and a suitable parameter, the localization factor defined. Estimates of this factor are made for both nuclear-bound and organically-bound tritium. Values of 4 and 1.5 respectively are suggested.

Organ uptake studies in rodents following long-term feeding of organically-bound tritium are compared. The tritium is found to be unequally distributed among the tissues studied. The highest specific activity occurs in liver, with the lowest in femur. The specific activity of tritium in tissue-free water slightly exceeds that of organically-bound tritium in liver.

Retention studies reveal a three-component exponential decrease of organically-bound tritium. No discernible trends of the periods of the three components with specific organs could be established. Average values of the periods are 1.2 ± .2, 10 ± 2, and 65 ± 8 days.

It is concluded that specific enhancement of radiobiological effectiveness due to incorporation of tritium in DNA does probably not occur.

The radiotoxicological impact of organically-bound tritium could warrant the use of a radiation weighting factor between 2 and 3.

RÉSUMÉ

Le présent rapport passe en revue la documentation et les données concernant la microdosimétrie, l'efficacité biologique relative, la distribution subcellulaire, l'incorporation par les organes et la rétention du tritium organique.

Selon les calculs qui sont fournis, le facteur de qualité du spectre de dégradation des électrons lié au champ de rayonnement bêta du tritium dans l'eau serait de 1,9 ± 0,2. On cite également une mesure de qualité expérimentale reliée de 1,6 ± 0,2 et une estimation de 1,3 d'après des études par simulation.

On a découvert que cette valeur moyenne de l'efficacité biologique relative pour une banque de données de 55 valeurs s'élevait à 1,8 ± 0,1. Le rapport aborde aussi l'influence des rayonnements de référence, les méthodes *in vivo* par rapport aux méthodes *in vitro*, ainsi que l'utilisation de la thymidine tritiée ou de l'eau tritiée.

Une technique utilisée pour prévoir les effets de la distribution subcellulaire est décrite et le facteur de localisation utilisé comme paramètre approprié est défini. Des calculs estimatifs de ce facteur sont donnés pour le tritium lié au noyau et le tritium organique. Des valeurs de 4 et de 1,5 sont suggérées respectivement pour chaque cas.

Le rapport compare aussi les résultats des études sur l'incorporation par les organes chez les rongeurs après avoir été nourris longtemps au tritium organique. On a découvert que le tritium n'était pas distribué également parmi les tissus à l'étude. L'activité spécifique la plus élevée se produit dans le foie et la moins élevée, dans le fémur. L'activité spécifique du tritium dans l'eau corporelle dépasse légèrement celle du tritium qui se loge dans le foie.

Les études sur la rétention révèlent une décroissance exponentielle à trois composantes du tritium organique. Aucune tendance discernable des périodes des trois composantes pour des organes précis n'a pu être établie. Les valeurs moyennes de ces périodes étaient de 1,2 ± 0,2, 10 ± 2 et de 65 ± 8 jours.

L'auteur du rapport conclut que l'amélioration précise de l'efficacité radiobiologique attribuable à l'incorporation de tritium dans l'ADN ne se produit probablement pas.

Les répercussions radiotoxicologiques du tritium organique pourraient nécessiter l'utilisation d'un facteur de pondération variant de 2 à 3.

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
1.	Introduction	1
1.1	Physical properties of tritium	1
1.2	Metabolic considerations	1
1.3	Radiation weighting factor	1
1.4	Subcellular distribution	3
1.5	Literature search	3
1.6	Project design	4
2.	Microdosimetry	4
2.1	Microdosimetric parameters	4
2.2	Experimental data	5
2.3	Simulation studies	6
2.4	Analytical calculations	7
2.5	Cross section and associated quantities	7
2.6	Energy distributions	9
2.7	The tritium quality factor	11
2.8	Mean free path, track average LET and average range	12
2.9	Discussion	13
3.	Dose Point Kernel	14
3.1	Introduction	14
3.2	Calculation	14
3.3	Microscopic absorbed fractions	15
3.4	Discussion	16
4.	Radiobiological Data	17
4.1	RBE data base	17
4.2	Analysis	17
4.3	Catergorizations	17
4.4	Discussion	18
5.	Microdistribution Effects	19
5.1	Introduction	19
5.2	Tritiated thymidine	21
5.3	Organically bound tritium	21
5.4	Discussion	22
6.	Uptake and Retention Studies	23
6.1	Tissue uptake distributions	23
6.2	DNA uptake	24
6.3	Retention times	26
7.	Conclusions	26
8.	Recommendations	28
9.	References	28
APPENDICES		
APPENDIX A	Bibliography	
APPENDIX B	Slowing Down Theory	
APPENDIX C	RBE Database	

EFFECTS OF MICRODISTRIBUTION OF TRITIUM ON DOSE CALCULATIONS

1. Introduction

1.1 Physical properties of tritium

The naturally occurring cosmogenic radionuclide ^{3}H beta decays to ^{3}He with a half-life of 12.3 y.[1] For this half-life the number of tritium nuclei per unit of activity is 5.6×10^{8} Bq^{-1}.

The total energy release in the ^{3}H decay is 18.6 keV.[1] The spins and parities of both the initial and final states of the decay are 1/2+ so that the beta spectrum is characterized by an allowed shape with an endpoint energy of 18.6 keV.

The average energy of a beta particle in the spectrum is 5.68 keV.[2] This corresponds to an equilibrium dose constant of 3.3 $\mu Gy \cdot kg \cdot MBq^{-1} \cdot h^{-1}$.

Because of their low energy, the beta particles of ^{3}H are weakly penetrating. The continuous-slowing-down-approximation (CSDA) range of the maximum energy beta particle is only about 8 μm and is thus comparable to subcellular dimensions. This not only has implications regarding the dosimetry of tritium but also renders routine monitoring of the activity difficult.

1.2 Metabolic considerations

In general released tritium initially is incorporated in water. Exposure to animals in organic form takes place through the intermediary of plants. The process is reviewed by Belot[3] and will only be summarized here. Aqueous tritium is easily exchanged with hydrogen atoms attached to oxygen, sulphur, or nitrogen atoms. The exchange process for these species takes place rapidly with equilibration times of the order of seconds. Tritium is bound to carbon by metabolic processes, primarily photosynthesis. Belot states that hydrogen atoms linked to carbon atoms fail to exchange at all.

In animals the digestion of large molecules of carbohydrates, proteins and fats results in hydrolytic cleavage to produce the smaller molecules corresponding to monosaccharides, amino acids and fatty acids. These compounds are incorporated into the pool of metabolic precursors and one of three processes follows. Firstly the compounds may be oxidized to form water. Secondly they may take part in the synthesis of functional body constituents such as enzymes, hormones, structural elements or secretion products. Finally they may be synthesized into the pool of body reserves. Generally a three-component retention is observed with periods of 1-2, 5-10 and 70-130 days for the three groups.[4]

1.3 Radiation weighting factor

In this report the value of the radiation weighting factor, w_R, for organically bound tritium is considered. The philosophy which guided the stratagem of the study is stated here.

The International Commission on Radiation Protection (ICRP) has recently[5] introduced the concept of a radiation weighting factor. This quantity essentially replaces the quality factor, Q, previously used to take into account the dependence of the probability of stochastic effects on the type and energy of the radiation field. The values of w_R are stated to be broadly compatible with the quality factor but have been introduced to eliminate an implied spurious precision inherent in the latter. Unfortunately it is not clear what limits are to be set with respect to precision for this new quantity. Since currently recommended values include unity for photons and five for neutrons with energy less than 10 keV, it is inferred that the precision is not restricted to order-of-magnitude. For this study we interpret the limit to be the nearest integer.

While the ICRP has replaced the quality factor for purposes of the calculation of the equivalent dose, they have also introduced a new relationship defining the explicit dependence of Q on the unrestricted linear energy transfer in water (LET_∞). Since w_R is meant to be broadly compatible with Q, it was decided that knowledge of this quantity for tritium was a necessary datum for consideration. Since no value for the tritium quality factor seems to have been estimated previously, even for the earlier Q-LET_∞ dependence, it was decided to perform the calculation as part of this study.

From a broader perspective, in this report we distinguish between the quality of a radiation field and the corresponding quality factor as follows. In experimental or theoretical investigations of the microdosimetric properties of radiation fields it is possible to measure or calculate several attributes which may be compared for differing fields. The relative values of such attributes which are thought to be relevant to the biological effectiveness are a measure of its quality. In keeping with traditional definition the reference radiation field is generated by 250 kVp X-rays. Two examples of such studies, one experimental the other theoretical, have been found and shed some additional light on the quality of tritium, as distinct from the uniquely defined quality factor discussed above.

The ICRP recommends that w_R be representative of the relative biological effectiveness (RBE) in inducing stochastic effects at low doses. Depending upon what one considers as a low dose, the unfortunate consequence of this restriction is to eliminate the bulk, if not all, of the radiobiological data. In this circumstance it would then be necessary to infer the effectiveness from an epidemiological approach. In light of recent experience, such an approach applied to the field of radiotoxicology seems to generate much more in the way of contention than information. To a large extent we feel that radiobiological studies, in common with most toxicology, must resort to higher levels of insult than strictly desirable in order to obtain any information at all. Criticisms of the details of specific RBE studies have been given elsewhere[6]. Suffice it to say that experimental uncertainties, biological variations and limited control of the very many parameters all contribute to fluctuations in the results.

In this study no attempt has been made to select or emphasize specific radiobiological studies or, except in one tentative estimate, to make corrections to the published results. In our opinion selection may

inadvertently introduce undesirable bias. Our approach has been to include as many results as possible and attempt to average over the inherent variations. In particular, in keeping with the recommendations of the ICRP, no distinction is made based upon whether the reference radiation is X- or γ-radiation. Evidence exists in general, however, that γ-radiation and x-radiation are not equivalent reference fields[6]. Inherent in this approach is the assumption that while individual endpoints are not those necessarily relevant to the desired effect, the relative ability of the radiation field to produce the latter is approximately indicated by this average.

1.4 Subcellular distribution

An additional complication in the study involves the possibility of inhomogeneous distribution of tritium within the biological material and indeed within the cell structure itself. In some sense inhomogeneity is a given fact at sufficiently low doses. For example, at a dose rate comparable to the natural background, one $mGy \cdot y^{-1}$, the resident activity based upon the equilibrium dose constant would be 33 $Bq \cdot g^{-1}$. This corresponds to an atomic concentration of approximately 2×10^{10} g^{-1}. Since cell concentrations are typically of the order of 10^{9} g^{-1}, this would imply that a cell would contain 20 tritium atoms. Similarly, for a dose of one mGy there would be an average of about one disintegration per cell. For this reason, in this work all distributions are considered to be within the framework of the cell population as an ensemble.

One consequence of such subcellular distributions is the fact that tritium can be incorporated within the structure of the DNA molecule itself. Since the DNA molecule is generally believed to be the primary radiosensitive material, this situation could be exceptional. In this report consideration has been given to the possible special implications of incorporation.

A second aspect of subcellular distribution effects arises from the fact that, as stated by the ICRP and in keeping with customary practice, the dose is evaluated as an average over the tissue of interest. If one considers the dose to the nucleus as critical however then such an approach may be inadequate. In order to investigate this point further the localization factor is introduced in this report and is defined as the ratio of the nucleoplasmic dose to the tissue average dose.

1.5 Literature search

Four separate literature searches were performed using different routines. The four search systems employed were:

Quest
Science Citation Index
International Nuclear Information Database
Nuclear Science Abstracts

The results of these searches, together with additional relevant references found in the primary sources, have been combined into a single bibliography. These have been sorted according to date and alphabetical order. The bibliography is listed in Appendix A.

1.6 Project design

To achieve the objective of this study the investigation was organized into a consideration of the following properties:

Quality of the tritium radiation field
The dose point kernel for tritium
Relative biological effectiveness
Subcellular distribution effects
Tissue uptake and retention

The first two items arise out of a general consideration of microdosimetric properties. Information regarding the quality of the radiation field was based upon the following:

Calculated quality factor
Experimentally determined specific energy
Electron track simulation of DNA double strand breakage

The information obtained above was then combined with the radiobiological data to obtain a final estimate of the general quality of the tritium radiation field.

Analysis of the nuclear dose for subcellular distributions of DNA-bound and more general organically bound tritium involves the dose point kernel and yields corresponding localization factors. These factors express the ratio of the critical quantity, nucleoplasmic dose, to the quantity in current use, average tissue dose. Based upon information regarding uptake characteristics for OBT an overall localization factor is then estimated.

The radiation weighting factor for OBT which is necessary for caulculating eqivalent dose, is then estimated as the product of the general quality with the overall localization factor.

2. Microdosimetry

2.1 Microdosimetric parameters

The fundamental quantity describing the interaction of an electron with matter is the differential cross section. For a complete description of the electron transport the cross sections for all interaction types are important. These include elastic scattering, inelastic scattering in which the target is left in a bound excited state and ionization. The last is the interaction most likely to lead to a significant biological effect, either directly or indirectly.

The quantity commonly used to describe the behaviour of an electron of energy E is the stopping power, S(E), which may be derived from the cross section under certain conditions. This quantity is also referred to as the linear energy transfer LET. The stopping power function for electrons propagating in material in the condensed state, also known as the energy loss function in this case, is not well-known over the entire range of energies. It is not possible to use the cross section data in this case because of the collective

response of the medium. In general such effects are limited to the region below a few keV and for higher energies the stopping power function is well-established.[7]

The biological effectiveness of a radiation field is known to be strongly correlated with the associated stopping power or linear energy transfer.[8] This correlation is expressed by the quality factor which essentially represents the average effectiveness and is determined by the stopping power in water.

The LET is energy dependent so that a unique value exists only for a mono-energetic radiation field. More generally, it is customary to employ the value averaged over the fluence spectrum, referred to as the track average LET. This quantity is important since it determines the relation between fluence and dose as will be demonstrated shortly. Related parameters are restricted linear energy transfers in which the range of energy losses is restricted to an upper limit of Δ, rather than the maximum which can occur in the collision processes. The restricted LET is designated L_Δ.

A quantity closely related to the track average LET is the average range. The track average LET is the ratio of the average energy of the fluence spectrum to the average range. Some authors appear to use the range evaluated at the average energy but this is not correct since the range-energy relationship is not linear.

2.2 Experimental data

Information regarding the microdosimetric properties of a radiation field may be obtained by using a low pressure proportional counter containing a tissue-equivalent gas. Normally the counter is spherical in shape and its effective dimensions at unit density equal the product of the physical dimensions with the density of the filling gas. In this way it is possible to simulate regions in tissue with dimensions on a subcellular scale.

An event resulting in the deposition of energy in the detector volume produces a pulse the height of which is proportional to the energy deposited. Provided the detector diameter is small compared to the particle range, the energy deposited is the product of the particle stopping power and the length of the chord generated by the intersection of the particle track and the detector volume. The observed pulse-height distribution thus reflects both the chord distribution and the linear energy transfer distribution.

While it is possible to correct the observed distribution to obtain the LET distribution, a sufficient approximation results from the lineal energy, defined as the ratio of energy deposited to the average chord length. For a sphere this is 2/3 of the diameter. In particular for diameters short compared to the range the mean lineal energy equals the LET. In this case the frequency average lineal energy is the track average LET.

An experimental study of this type involving tritium was performed by Ellet and Braby[9]. These authors substituted propane for the usual tissue equivalent counting gas in order to increase the signal-to-noise ratio. Tritiated methane was mixed with the propane so that the source was uniformly distributed within the chamber. Since signal strength decreases with pressure there is a lower

limit imposed on the effective dimension. The smallest effective diameter for which event spectra were recorded was 0.6 μm but the spectrum was not presented. The smallest effective diameter for which a spectrum is shown is 0.92 μm.

For the 0.92 μm-diameter sphere the spectrum exhibited a modal value of about 4 keV$\cdot\mu$m^{-1} and a median value of 2.4 keV$\cdot\mu$m^{-1}. For 65 kVp X-rays the corresponding values were found to be 1.5 and 1.1 keV$\cdot\mu$m^{-1}. The dose delivered by tritium was concentrated in a relatively narrow range of lineal energies with half the energy being delivered by events between 3.0 and 7.2 keV$\cdot\mu$m^{-1}. The frequency average lineal energy was 3.8 keV$\cdot\mu$m^{-1} for the smallest diameter measured. The results of this experiment are summarized in table 1. According to the theory of dual radiation action,[10] the biological effectiveness of the radiation field is proportional to the dose average specific energy in the limit of low doses. The value of this quantity was determined in this experiment for a variety of radiation fields. Based on the value for tritium relative to 250 kVp radiation with an HVL of 1.8mm Cu, they estimate a relative effectiveness of 1.6 ± .2 for sites of 0.6 μm diameter and 1.5 ± .2 for 1.0 μm diameter, for doses much less than 4 Gy. They find corresponding values of 1.4 ± .1 for both sites for 65 kVp radiation. For ^{60}Co the relative effectiveness is found to be only 0.5 and 0.4 for the 0.6 and 1.0 μm diameters respectively.

Table 1: Dose Average Specific Energies $\bar{\zeta}$ (from Ref. 9)

	$\bar{\zeta}$ (Gray)			
Diameter (μm)	^{60}Co	250kVp	65 kVp	^{3}H
0.6	12.0	25.0	35.0	39.0
1.0	3.2	7.6	11.0	11.0
2.0	0.6	1.6	2.0	2.0
3.0	0.22	0.58	0.74	0.66
5.0	0.066	0.17	0.22	0.17

2.3 Simulation studies

The consequences of irradiation with any field may be investigated using Monte Carlo techniques. Such calculations are in principle extremely powerful. Provided the basic data are available it is possible to simulate processes such as molecular ionization, free radical production and diffusion on a nanometer scale. For electron transport the methodology of condensed histories is normally used as typified by the EGS and ETRAN codes. These are more suitable for higher energies than are typical for tritium. Recently codes have been developed which follow individual interactions.

Ito[11] has performed track structure simulations for electrons generated from ^{60}Co γ-rays, 280 kVp X-rays, ^{3}H beta decay and for 523 eV δ-rays, using the

code ETRACK. He has calculated the intratrack and intertrack proximity functions and the lineal energy behaviour. The latter is said to be consistent with the experimental results.

The author states the number of single strand breaks in a cell nucleus is estimated to be 580 Gy^{-1}. The calculations indicate 360 Gy^{-1} from direct ionization and 235 Gy^{-1} from OH· radicals. Ito calculates the ratio of double to single strand breaks for the radiation types studied. This ratio decreases from 3.12% for the lowest energy radiation (523 eV δ-rays) to 1.56% for the highest (^{60}Co γ-rays). For tritium the value is 1.76% corresponding to a quality factor of 1.3. Three modes of double strand breaking are possible; both breaks result from direct ionization, one lesion is caused directly while the second is indirect arising from free radical production and finally both are produced indirectly. The relative probabilities of the three modes are calculated to be 0.88, 1.06 and 0.02.

2.4 Analytical calculations

Estimates of relevant microdosimetric parameters may be made by numerical techniques using slowing down theory, the details of which are described in Appendix B. As stated above, the primary information required includes appropriate cross sections, the stopping power and the electron energy distribution. The calculations described here are for propagation in water.

The electron spectrum is only unique under two circumstances - propagation from any source distribution in vacuo, and propagation in a material medium from a uniform source distribution. It is the latter case which is considered here. The fundamental physical basis for the calculation is that at any point in the radiation field contributions to the fluence spectrum are made equally from electrons at all stages in their life history. From this viewpoint the requirement of uniformity is not unduly restrictive. If one considers the situation of a point source (such as a single atom) located in a cell nucleus, it would at first sight seem that the above spectrum would not be relevant. This is not the case however for two reasons. Firstly, while the source distribution is indeed far from uniform, the target, i.e. the DNA, may be normally distributed roughly uniformly throughout the nucleus[12]. An interaction between the emitted electron and the DNA may occur, therefore, with essentially equal probability at any point along the track, in keeping with the above basis of the calculation. Secondly, the computation must be viewed as a statistical one with the cell population as the ensemble. The location of the tritium will be randomly distributed in the nucleus and hence is uniform over the ensemble.

2.5 Cross section and associated quantities

The electron impact ionization cross section for water used in this work is described quantitatively in Appendix B, Equation (B12). The variation of the attenuation coefficient over the energy range of the tritium spectrum is shown in Figure 1. The threshold energy for ionization is 12.6 eV. The attenuation coefficient rises to a maximum of 0.6 nm^{-1} at 100 eV. At this energy the mean free path for an ionization is only 1.7 nm.

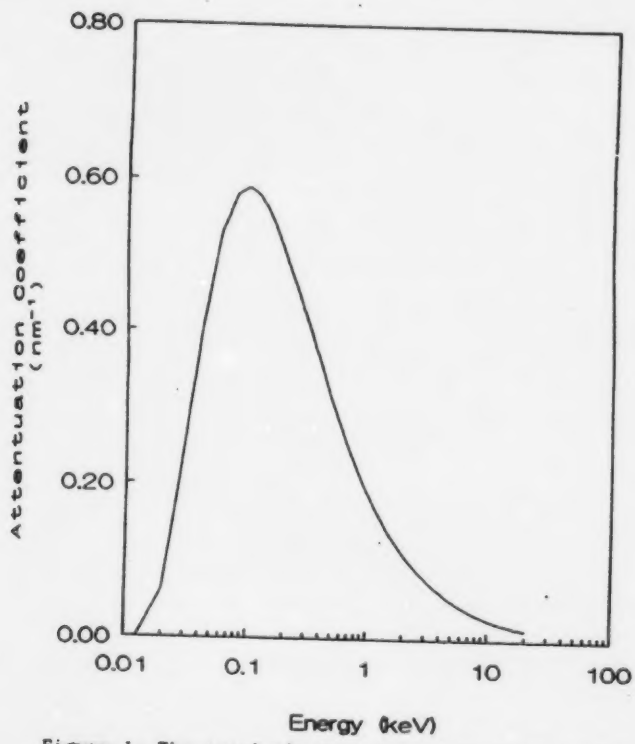

Figure 1: The total electron impact ionization attenuation coefficient for water in the energy region of tritium β-rays.

The behaviour of the electron stopping power in the region below 10 keV is not well defined since in this region the Born approximation upon which the usual Bethe formula rests is no longer valid. The stopping power for water used in the calculation is shown in Figure 2 and is an analytical representation of the results of Ashley[13]. As may be seen in the figure, this quantity rises to a maximum of about 27 keV/μm at 150 eV.

The quality factor is an explicit function of the unrestricted stopping power of water given above. The explicit dependence on LET recommended in ICRP 60[5] is given by

$$\begin{aligned} Q &= 1.0 && S < 10 \text{ keV}/\mu\text{m} \\ Q &= .32 \cdot S - 2.2 && 10 \leq S \leq 100 \text{ keV}/\mu\text{m} \\ Q &= 300/\sqrt{S} && S > 100 \text{ keV}/\mu\text{m} \end{aligned} \qquad (1)$$

Because the stopping power is an explicit function of energy the above equations result in an implicit dependence of the quality factor on energy. This dependence was calculated from the relations in Equation (1) and is illustrated in Figure 2. As may be seen from the figure, the quality factor exhibits a maximum of about 6 at 150 eV.

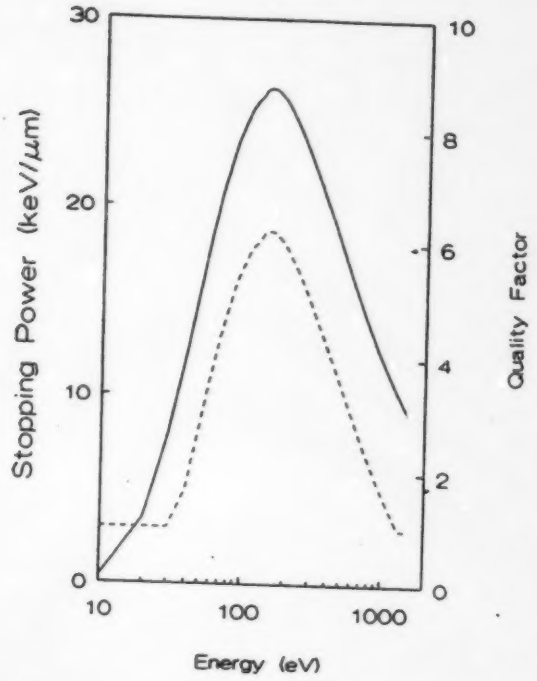

Figure 2: The variation of the electron stopping power in water with energy is shown by the solid curve. The corresponding quality factor calculated by the ICRP60 formulation is represented by the broken curve.

2.6 Energy distributions

The fundamental distribution characterizing tritium is the spectrum of electrons created in the decay process, referred to here as the emission spectrum. The emission spectrum is governed by the beta decay transition probability, p(E) which may be written

$$p(E) = F(Z,W)\cdot\eta\cdot W\cdot(E_o-E)^2 \qquad (2)$$

The first factor is the Fermi function. This depends upon the daughter atomic number Z, which is two in this case. The Fermi function also depends upon the total energy, W, which is the sum of the kinetic energy and the rest mass energy. The second term, η is the electron momentum. It should be mentioned that there is some controversy concerning the shape of the emission spectrum arising from the suggested existence of a massive neutrino with rest mass energy of 17 keV. The influence of this possible effect is less than 0.1 % so that it may be ignored in practice.

The spectrum calculated according to Equation (2) is illustrated in Figure 3. The average energy calculated by numerical integration of the computed spectrum is 5.7 keV in good agreement with the accepted value of 5.68 keV. The primary fluence spectrum $\phi(E)$ generated at a point in a material medium by tritium decay differs from the emission spectrum $p(E')$ because electrons produced at a remote site lose energy by inelastic collisions as they propagate to the point under consideration. This spectrum of degraded electrons, the slowing down spectrum, may be derived using transport theory in

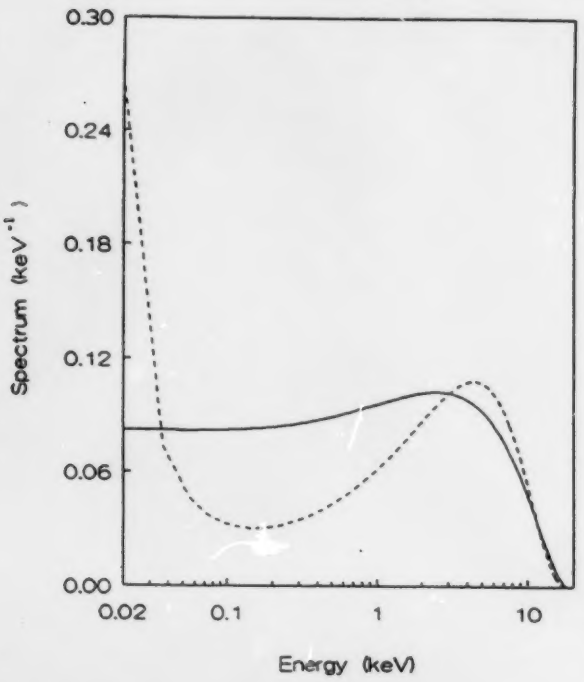

Figure 3: The solid curve illustrates the spectrum of β^- particles emitted in the decay of tritium. The broken curve depicts the resultant electron slowing down spectrum according to the CSDA.

the continuous slowing down approximation for a uniformly distributed source as explained in Appendix B. The result is

$$\phi(E) = \left(\int_E^{E_o} p(E') \cdot dE' \right) \cdot S^{-1}(E) \qquad (3)$$

The usual dimensions of the fluence spectrum are cm^{-2} keV^{-1}. These arise for a specified source strength. Since only the shape of the spectrum is relevant here, it is not necessary to calculate absolute values.

The primary fluence spectrum of degraded electrons calculated according to Equation (3) is compared with the emission spectrum in Figure 3.

The complete degradation spectrum may be considered to consist of three components:

1. The degraded beta particles
2. Delta-rays produced by impact ionization
3. Auger electrons emitted by K-shell ionization de-excitation.

The latter two components are also degraded as they propagate from their point of origin. The first component is the primary fluence spectrum calculated using the continuous slowing down approximation in Equation (3). The second and third components are calculated from their respective production spectra

in a similar manner. A more detailed discussion is given in Appendix B. The calculated electron degradation spectrum in water together with the three components are shown in Figure 4. The contribution from δ-rays exceeds that of the primary spectrum for energies below approximately 0.3 keV and dominates the low energy region. The contribution from Auger electrons is generally insignificant amounting to some 10% in the most sensitive region near 0.5 keV.

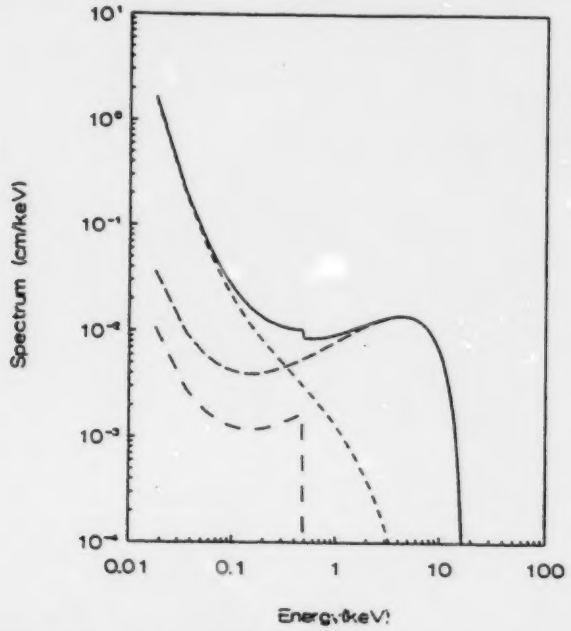

Figure 4: The electron degradation spectrum of tritium. The short broken line falling steeply with increasing energy represents the contribution from δ-rays. The small Auger component is shown as the long broken line, cutting off sharply at 0.49 keV. The third component corresponds to the primary slowing down spectrum. The sum of the three contributions is shown by the solid line.

2.7 The tritium quality factor

The fundamental equation for dose equivalent, H, is

$$H = \int Q \cdot dD \qquad (4)$$

where dD is the element of dose contributed by radiation of quality Q. For convenience the calculation will be performed for water, a medium with unit density and dosimetric properties similar to soft tissue.

For unit density media equation (4) can be written in terms of the electron fluence spectrum, $\phi(E)$, to give

$$H = \int Q \cdot S(E) \cdot \phi(E) \cdot dE \qquad (5)$$

In Equation (5), S(E) is the stopping power for an electron of kinetic energy E and the integration extends over the energy range from 0 to the maximum value E_o. The tritium quality factor is then given by

$$Q_t = H/D \qquad (6)$$

The quality factor calculated by numerical integration for the 1000-point electron degradation spectrum of Figure 4, using the LET dependence recommended by ICRP 60, is

$$Q_t = 1.9 \pm .2$$

This value is to be compared with the result of

$$Q_t' = 1.4 \pm .2$$

obtained using only the primary component of the spectrum. The increase results from the fact that the additional δ-ray component is concentrated in the region of relatively high LET. It is of significance that the value obtained from the complete spectrum is approximately equal to that obtained for the emission spectrum, 1.8. On this basis it is reasonable to assume that this parameter would be relatively stable under non-equilibrium conditions.

2.8 Mean free path, track average LET and average range

The inverse of the electron impact ionization attenuation coefficient illustrated in Figure 1 is the mean free path. This quantity was averaged over the emission spectrum of Equation (2). The average value was found to be

$$\langle mfp \rangle = 22 \text{ nm}.$$

For comparison the diameter of DNA is only 2 nm.
For a fluence spectrum $\phi(E)$, the track average LET is given by

$$\langle L \rangle = \phi^{-1} \cdot \int_o^{Eo} \phi(E) \cdot S(E) \cdot dE \qquad (7)$$

where the total fluence is given by

$$\phi = \int_o^{Eo} \phi(E) \cdot dE \qquad (8)$$

The integral in Equation (7) is the energy loss density. For a unit density medium in charged-particle equilibrium this quantity is equivalent to the dose. The inverse of $\langle L \rangle$ may therefore be used to calculate the fluence corresponding to a unit dose.

For the electron degradation spectrum depicted in Figure 4 the unrestricted track average LET was found to be

$$LET_\infty = 5.0 \pm .5 \text{ keV} \cdot \mu\text{m}^{-1}$$

corresponding to the value of $\langle L \rangle$ in Equation (7) when S(E) is the unrestricted stopping power. The corresponding fluence-to-dose ratio is

$$\Phi = 1.3 \times 10^{8}\ \text{cm}^{-2} \cdot \text{Gy}^{-1}.$$

For completeness, the value of LET for energy losses restricted to a maximum of 0.1 keV was also estimated. This quantity is often used in radiobiology. In this case the restricted stopping power[7] was used in the integral in Equation (7) to obtain

$$\text{LET}_{0.1} = 4.0 \pm .4\ \text{keV} \cdot \mu\text{m}^{-1}$$

The mean range for the emitted electrons was calculated by averaging the range-energy relation over the emission spectrum. The range-energy relation in this energy range was taken from Ito[11]. The resulting value for this quantity is

$$\langle R \rangle = 1.3\ \mu\text{m}.$$

It may be shown from continuous slowing down theory that the track average LET_{∞} for the primary electrons is the ratio of the average energy and average range for the emission spectrum. On this basis the track average LET_{∞} for the primary electrons is 5.7/1.3 or about 4.4 $\text{keV} \cdot \mu\text{m}^{-1}$. When secondary electrons are taken into account this is seen to be increased by some 14%. Similarly if secondary electrons are included in the range estimate the mean range is calculated to be 0.89 μm.

2.9 Discussion

The experimental and calculated results (given in subsections 2.2 and 2.8 respectively) pertaining to LET are not directly comparable. The mass stopping power of propane differs from that of water. While the behaviour of the former is not known at low energies, the value for water at 10 keV is 86% that of propane. Since for gases the mass stopping power ratio is relatively insenstive to energy this value will be assumed to hold over the entire range. Correction for this effect gives a value for the frequency average lineal energy of 3.2 $\text{keV} \cdot \mu\text{m}^{-1}$ for the 0.6 μm diameter tritium data. This is considerably lower than the values of track average LET estimated by analytical calculations. The experimental values are distorted however since the minimum diameter used is not negligible compared to the particle range. Indeed for a significant fraction of the electrons the diameter exceeds the range. In this case the energy deposited is the entire energy and no longer proportional to chord length. The value measured now underestimates the average LET by the ratio of the range to the mean chord length.

The conclusions reached by Ellet and Braby[9] regarding the relative effectiveness of the different radiation fields studied are significant. Qualitatively the trends are consistent with those stated in NCRP report #63[6]. The effectiveness of ^{60}Co radiation is significantly less than that of the standard 250 kVp field while that for tritium closely matches the 65 kVp field. The value of 1.6 ± .2 found by Ellet and Braby[9] for tritium must be

considered to be in excellent agreement with that estimated here, particularly in view of the bias towards low values mentioned above.

In contrast, the relative effectiveness of ^{60}Co, 250 kVp X-rays and tritium based upon the double strand breaking estimates of the Monte Carlo simulations are less varied. Relative to 250 kVp X-rays, ^{60}Co radiation is calculated to have an effectiveness of 0.9, while the value estimated for tritium is only 1.3.

3. Dose point kernel

3.1 Introduction

The dose point kernel is required in the estimation of dose distributions. Since the dose-source relationship is linear, the dose resulting from a collection of sources is the sum of their individual contributions. A source which is spatially distributed may be decomposed into an infinite number of point sources.

The dose point kernel is the dose distribution K(R) produced by a unit activity point source. The quantity R represents the distance between the point source and the point at which the dose is evaluated.

If a source is distributed so that the activity per unit volume at position r' is $A(r')$, then the dose produced at r is

$$D(r) = \int K(R) \cdot A(r') \cdot d^3r' \qquad (9)$$

In the above integral

$$R = |r - r'| \qquad (10)$$

Thus the dose distribution results from the convolution of the activity concentration with the dose point kernel.

3.2 Calculation

As stated above, the distribution of deposited energy around a point source is fundamental in calculating general dose distributions. Since analytical solutions to the transport equation which take into account energy deposition fluctuations do not exist, the use of Monte Carlo simulation is required. In the work reported here, the energy deposition profile for a point source of tritium is calculated from data obtained using the condensed history simulation technique.

As described in detail elsewhere[14], an analytical expression was developed describing the energy deposition pattern, M(E,R), generated by Monte Carlo methods for monoenergetic electrons with energies from .5 to 18 keV. The tritium point source dose distribution was then calculated from

$$K(R) = \int M(E,R) \cdot p(E) \cdot dE \qquad (11)$$

The result is shown in Figure 5.

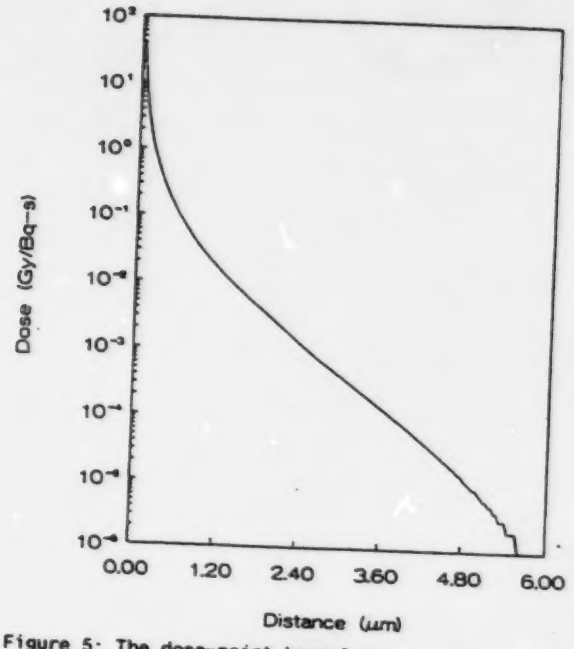

Figure 5: The dose-point kernel for tritium.

3.3 Microscopic absorbed fractions

As can be seen in the figure, the dose produced by the decay of a tritium atom is spread by electron transport over distances comparable to the dimensions of cell nuclei. This aspect is illustrated in Figure 6 which indicates the fraction of energy deposited in a cell nucleus by a point tritium source located at the center as a function of the nuclear diameter. This is an extreme case of course and it is expected that the fraction retained would be considerably lower for other situations. The distribution of tritium incorporated into DNA is more likely to be approximately uniform throughout the cell nuclear volume. For low levels of tritium such that only a few tritium atoms are incorporated in a given cell nucleus, the distribution referred to must be considered as an ensemble average over the cell population. The fraction of energy deposited in a spherical volume for such a uniformly distributed source of tritium has also been calculated for the dose point kernel of Figure 5 and is compared with that for a central point source in Figure 6 for the range of diameters typical of cell nuclei. For a cell with a nuclear diameter of 7 μm as an example, the fraction of energy deposited for a uniformly distributed source is about 73% while for the central point source it is about 90%. The discrepancy of some 17% indicates that the fraction is not highly sensitive to the details of the micro- distribution. We conclude that treatment assuming a uniform concentration throughout the cell nucleus for any incorporated tritium would be accurate to within 10%.

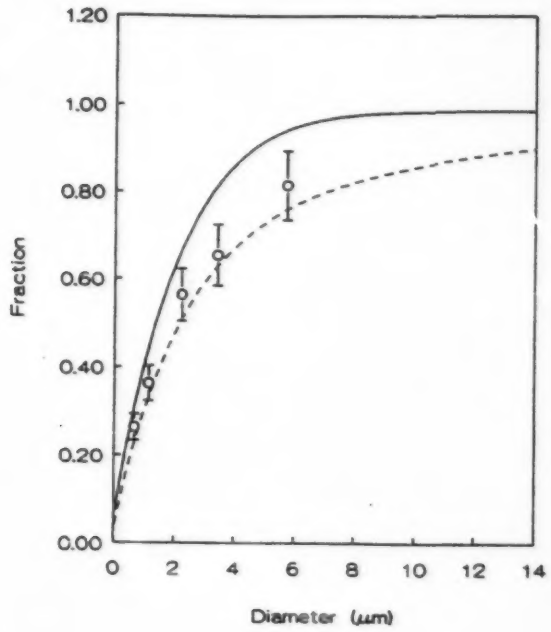

Figure 6: Fraction of tritium decay energy absorbed in spherical volume as a function of diameter. The upper curve illustrates the fraction absorbed for a point source at the center of the sphere. The broken curve shows the fraction absorbed for a uniform activity distribution in the volume. The data points are calculated from the experimental results of Ref. 9.

3.4 Discussion

The dose point kernel calculated here is in good agreement with that of Ito[11] except near the region beyond 4 μm. At this point the two calculations diverge significantly with our values lying lower. The result obtained by Ito indicates a more disperse dose distribution than that obtained here. It is expected therefore that the absorbed fractions calculated on the basis of his results would be lower than those obtained here. Our values are in good agreement with those obtained by Berger[14].

Independent evidence regarding the absorbed fraction for a sphere of uniform activity may be obtained by the experimental work of Ellet and Braby[9]. The event frequency average energy deposited is directly related to the mean lineal energy. Therefore the ratio of this quantity to the average energy, 5.7 keV is the fraction absorbed in the propane spheres. Because of the shorter range in propane an estimate must be made to correct the data. Since the absorbed fraction is explicitly dependent upon the ratio of range to sphere diameter the data were incorporated by using a corrected sphere radius. Based upon the assumption of a constant mass stopping power ratio of 0.86 for water to propane, it was assumed that the effective water diameter was the experimental value divided by this ratio. The estimates obtained in this manner are compared with our calculated values in Figure 6. The agreement is satisfactory although the data are consistently high. This trend is in opposition to that which would result from greater dispersion as in the Ito[11] calculation.

4. Radiobiological data

4.1 RBE data base

The review of the radiobiological literature since 1956 reveals 55 values determined for RBE which have been incorporated into a database. The cellular systems studied include eukaryotic cells such as L5178Y, confluent $10T_{1/2}$, small intestine epithelium and oocyte mouse cells, V59B chinese hamster cells, human fibroblast, HeLa, bone marrow stem and sperm cells, and prokaryotic cells of strains of *E.coli* bacteria. In addition, adult mice, mice embryos, rats, *Drosophila*, *Medaka*, and *Vicia* seedlings have been investigated.

At the cellular level, endpoints of cell killing, mutation frequency, DNA scissions, and inhibition of DNA replications have been used. For entire organisms pathologies of myeloid leukemia induction in CBA/H mice, spleenic and thymic weight loss, ^{59}Fe uptake and LD_{50} in mice and mammary tumor induction in rats have been employed as endpoints.

Compounds used include HTO, tritiated thymidine and tritiated amino acids. Normally these are introduced into the culture medium for cell studies. For intact organisms they are incorporated into food or water or introduced by intraperitoneal injection.

The attributes considered for each study were endpoint, organism, cell line, nuclear diameter, temperature, tritium compound, characteristic dose such as D_0, reference radiation, and dose rate. Not all attributes could be determined for each study. A condensed report of the contents of the data base listing those attributes for which information is complete, is given in Appendix C.

4.2 Analysis

The data were analysed using a log-normal model. In choosing this distribution we were guided by the ubiquitous applicability of this model to natural phenomena involving continuous variates with domain restricted to the positive real numbers. In addition we relied upon the general principle of the central limit theorem applied to processes which result from the multiplicative combination of a large number of independent random factors. The data are compared with the fitted model in Figure 7. The agreement is satisfactory. The fitted distribution corresponds to an average value for RBE of

$$\langle RBE \rangle = 1.8 \pm 0.1$$

where the uncertainty reflects the statistical variation only. The arithmetic mean and error estimate were also $1.8 \pm .1$ so that it may be concluded that this parameter is insensitive to the model of the distribution used here.

4.3 Categorizations

The paucity of data prevents a complete multivariate analysis of the results. A less detailed study was performed based upon the following categorizations of the data :

In vivo or in vitro study

X-ray or γ-ray reference radiation

Tritiated water (HTO) or tritiated thymidine (^{3}HTdR) exposure.

For the first categorization the mean values of RBE were found to be 1.8 ± .1 and 1.9 ± .2 for the in vivo and in vitro studies respectively. For the second categorization the values were 1.5 ± .2 and 1.8 ± .1 for X-ray and γ-ray studies respectively. For the third categorization the results were 1.7 ± .1 and 2.5 ± .6 corresponding to HTO and ^{3}HTdR labelling respectively.

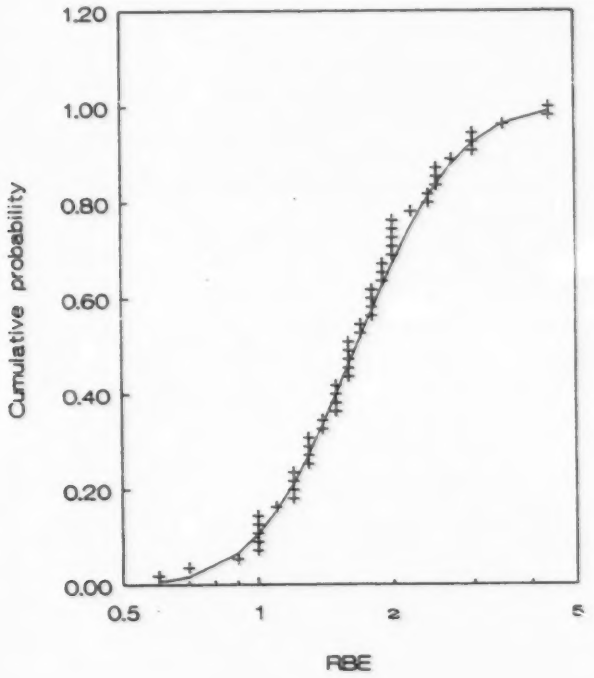

Figure 7: The cumulative probability distribution of observed relative biological effectiveness (RBE) of tritium β-radiation. The smooth curve is the cumulative probability for a log normal distribution with the same mean and variance as the data.

4.4 Discussion

The mean value of the entire data set is in good agreement with the quality factor estimates obtained by analytical calculation and microdosimetric experimentation outlined in Section 3.

No significant difference exists between the results of in vivo and in vitro studies.

The value for the radiation weighting factor is to be based upon the observed values of RBE, regardless of whether the reference radiation is X- or γ-radiation[5]. It has been pointed out however[6] that in general the RBE for these two radiations differ. The result obtained here indicates no statistically significant difference between the two data sets. Unfortunately the X-ray data is sparse so that the uncertainty for this value is relatively

large. The estimate of the effect given in the above reference suggests that the RBE for gamma radiation be corrected by a factor of 0.8. Such a correction results in a value of 1.5, which is in good agreement with the observed mean. In any event the data indicate that the use of data based upon either reference radiation is justified to an accuracy of 20%.

The third categorization is especially important since it bears upon the question of possible enhanced effects due to incorporation into DNA. Since thymine is the only base unique to DNA the use of ^{3}HTdR results in specific labelling of what is generally accepted to be the most radiosensitive site. It should be noted therefore, that in these studies autoradiography has been used to obtain estimates of the dose to the nucleus. The average value of RBE obtained from ^{3}HTdR studies is statistically larger than that for HTO labelling by a factor of 1.5 ± .3.

The difference between RBE values for the two types of labelling is not unequivocal evidence for an enhanced effect for incorporation. Of the eight values which make up the data set for ^{3}HTdR labelled exposures, four were performed at -195°C. While a complete delineation of temperature effects is not available, a comparison was made in the study reporting the above four results[16]. In one case a direct comparison was made of an otherwise identical treatment with temperatures of -195°C and 5°C. The RBE was observed to decrease from 3.0 to 1.8 with the increase in temperature. If the four data values are corrected by the same factor of 0.6, then the mean RBE value decreases to 1.7 ± .3. Such a correction is tentative at this stage but it does indicate the possibility of a significant distortion of the mean value for ^{3}HTdR studies and that incorporation effects probably do not significantly change the RBE at common cell temperatures.

5. Microdistribution Effects

5.1 Introduction

Two important publications investigating the microdistribution and its influence on dosimetry have essentially employed the methodology of internal dosimetry on the cellular scale.[17,18] The formulation will be outlined here using a slightly different nomenclature. The basic assumption is that the cell may be treated as two uniform substructures, the cell nucleus and the extranuclear region. The tritium distribution within each substructure is considered to be uniform. The critical quantity is identified as the average dose to the cell nucleus. As pointed out by Younis and Watt[19] this approach may in part be justified for the following reasons. First, while the average range of the tritium radiation is comparable to cell nuclear dimensions it is still relatively large on the molecular scale. Thus the resultant ionization damage from a tritium decay is spread over a region approaching the nuclear radius and direct damage is no more probable from a radionuclide incorporated into the DNA than from one in a nearby water or protein molecule. Secondly, the indirect damage which results following further migration of free radicals produced along the track is even more diffuse and hence more uniformly distributed. Finally while the radiosensitivity of DNA is well established it has been suggested that the integrity of the nuclear membrane may also be a critical factor. The only distinctive highly localized consequence of incorporation is that of transmutation.

The specific cumulative activities in the extranuclear and nuclear regions are designated $\tilde{A}_e$ and $\tilde{A}_n$. These quantities are understood to have dimensions corresponding to the number of disintegrations per unit mass such as $Bq \cdot s \cdot kg^{-1}$. The nucleus now receives two contributions referred to here as the self dose and external dose. The self dose corresponds to the energy per unit mass generated by decays within the nucleus corrected for the energy lost from the region by radiative transport. Similarly the external contribution corresponds to the energy per unit nuclear mass transported into the nucleus from the extranuclear region.

The analysis is obviated by considering the activity distribution to consist of a constant term $\tilde{A}_e$ throughout the entire cell and an activity excess $\tilde{A}_n - \tilde{A}_e$ concentrated in the nuclear volume. For a nuclear diameter d, the fraction of energy absorbed, f(d) is determined from the dose-point kernel as described in Section 2. The dose to the nucleus due to the constant term is then equivalent to that for an equilibrium dose and the details of the transport need not be considered. The resulting nuclear dose can thus be written

$$D = \left[\tilde{A}_e + (\tilde{A}_n - \tilde{A}_e) \cdot f(d)\right] \cdot E \qquad (12)$$

In the above equation E is the average energy release per decay, given as 5.7 keV. The above can be rearranged to give

$$D = \left[\tilde{A}_e \cdot [1-f(d)] + \tilde{A}_n \cdot f(d)\right] \cdot E \qquad (13)$$

The expression in Equation (13) is now compared with that which corresponds to the case for which tritium is considered to be uniformly distributed. The effective uniform specific cumulative activity is given by

$$\tilde{A}_u = (1-w) \cdot \tilde{A}_e + w \cdot \tilde{A}_n \qquad (14)$$

where w is the fraction of tissue mass corresponding to nuclei. The equilibrium dose estimate is simply

$$D_u = \tilde{A}_u \cdot E \qquad (15)$$

Since the latter is the normal dose estimate it is convenient to introduce a localization factor, L, defined as the ratio of the dose given in Equation (13) to the equilibrium dose. Thus

$$L = [1-f(d)] \cdot \tilde{A}_e / \tilde{A}_u + f(d) \cdot \tilde{A}_n / \tilde{A}_u \qquad (16)$$

The localization factor defined in Equation (16) depends upon both cytological and biochemical parameters. The cytological parameters are the diameter of the cell nucleus and the fraction of tissue by weight corresponding to nuclear

material. The biochemical parameter is the ratio of specific cumulative activity concentration in the extranuclear region of the cell to that in the nucleus $\bar{A}_e/\bar{A}_n$.

5.2 Tritiated thymidine

In the first of the two experiments mentioned above, Saito et al.[17], pregnant mice were given tritiated thymidine. The resultant off-spring were then nursed by non-exposed mothers. The specific activity of DNA was determined just after birth and at ages of one, two and four weeks, for spleen, kidney, brain, liver, intestine, heart and lung. For each of the first six, diameters of cell nuclei were determined and found to range from 5.6 μm for the spleen to 8.7 μm for the intestine. The nuclear mass of DNA was determined for spleen, kidney, brain, and liver cells and estimated for the rest. The dose calculated from the specific cumulative activity in the nucleus, corrected for energy escape, was then compared with the equilibrium dose based upon the measured uniform specific cumulative activity. The latter is referred to as the tissue-average specific cumulative activity.

Because DNA-bound ^3H contains little, if any, ^3H in exchangeable form[20], in this situation there is essentially no external concentration of tritium, so $\bar{A}_e = 0$. The localization factors varied from a minimum of 1.5 for intestine to 6.2 for brain. No error estimates are given.

5.3 Organically bound tritium

In the second study[18] the effect of the microdistribution of organically-bound tritium was investigated. In this study the concentration of protein in the cell nucleus and in the external region was determined for spleen, kidney, liver and brain. The tritium specific activity was assumed to be proportional to the protein concentration. In this case the localization factors were found to be much smaller, ranging from 0.84 in brain to 1.54 in spleen, with a geometric mean of 1.3. The results are given in more detail in Table 2.

Table 2: Localization factors for OBT[18]

	Spleen	Liver	Kidney	Brain
P_n/P_t*	1.8	1.4	1.7	0.8
P_e/P_t*	0.8	1.0	0.9	1.0
d(μm)	5.6	8.1	6.8	8.5
f(d)	0.75±.03	0.82±.03	0.79±.04	0.82±.05
L	1.54±.04	1.33±.01	1.53±.03	0.84±.01

*P_n, P_e, and P_t are the nuclear, extranuclear and tissue-averaged protein concentrations.

5.4 Discussion

The values of the localization factors depend critically upon the nuclear mass fraction designated μ. This quantity is not directly quoted in the above papers but may be inferred from the results. Moreover, the value may be compared in the two works for corresponding tissues. This is of interest since quite different methodologies were used and the inferred value is independent in each case. In the thymidine study the value of μ is obtained as the ratio of effective uniform specific activity to nuclear specific activity. In the OBT study, μ is obtained as the product of the number of nuclei measured per unit tissue mass, the density of nucleoplasm and the nuclear volume. The errors in this latter parameter are stated as about 50% and are not included in their stated uncertainties for the localization factors.

The nuclear mass fraction is closely related to the nucleocytoplasmic volume ratio $R_{n/c}$ defined as the ratio of nucleoplasmic to cytoplasmic volume. Taking the densities of nucleoplasm and cytoplasm to be identical and assuming the cell mass to be indicative of tissue mass

$$\mu = R_{n/c} \cdot [1 + R_{n/c}]^{-1} \qquad (17)$$

Recently[21] a sensitive fluorometric method has been developed to determine the $R_{n/c}$ and has been applied to a series of cultured cells. The cells studied were bovine aortic endothelial cells (BAED), Swiss 3T3 fibroblasts, PtK_2 cells and CV-1 cells. By measuring large numbers of replicate cells, of the order of 80, the study indicated the natural variability of this quantity which was found to be of the order of 5%. Unfortunately these authors do not state corresponding nuclear diameters so these parameters had to be estimated from cell volumes indicated on a graph.

In Table 3 is summarized the data of Saito as well as the more accurate cytofluorometric data mentioned above. The localization factors for the latter were calculated in this work.

Table 3: Localization factors for nuclear bound tritium

	μ		d(μm)	f	L
	[ref 17]	[ref 18]			[ref 17]
Spleen	0.23	0.23	5.6	0.75	3.2
Liver	0.16	0.08	8.1	0.82	5.1
Kidney	0.26	0.08	6.8	0.79	3.0
Brain	0.13	0.11	8.5	0.82	6.1
	[ref 21]				
BAED	0.17		9	0.82	4.8
3t3	0.23		11	0.86	3.7
PtK2	0.21		11	0.86	4.1
CV-1	0.24		11	0.86	3.6

As can be seen in Table 3, the values of ν determined for spleen and brain are in good agreement in the two studies. The values for liver and kidney however are different by factors approaching three. It is to be noted that the localization factors are based upon the higher values, so that if the lower estimates were used the values for L would be increased dramatically for these tissues. In addition it should be noted that in the thymidine study a value of 1.5 for the localization factor of small intestine cells is quoted. This would imply a nuclear mass fraction of 0.55 for these cells. Unfortunately it was not possible to ascertain experimentally the DNA content in this case and a value of 7.0 pg was assumed. The implied value of ν seems high compared to the values appearing in Table 3. The entries in the table are restricted to those for which there is an experimental basis. The mean localization factor calculated assuming a lognormal distribution is

$$\langle L \rangle = 4.1 \pm 0.2.$$

For comparison the arithmetic mean is $4.2 \pm .4$.

6. Uptake and retention studies

6.1 Tissue uptake distributions

In this section studies involving the distribution of ^3H with respect to tissue type following ingestion of organically bound tritium (OBT) are considered.

The first study described was performed by Komatsu et al.[20] In this investigation month-old mice were fed organically bound tritium in the form of tritiated brine shrimp added to commercial fodder. The specific activity distribution of OBT was determined for testis, muscle, small intestine, liver, brain, fat and tissue-free water (TFWT). The results are listed in Table 4. The data were taken after seven days of the regimen.

A second experiment involving mice was carried out by Golnik and Rochalska.[22] In this case the standard diet was supplemented with lyophilised, powdered tissues containing OBT. The OBT supplement was prepared from foetuses and some organs of female rats which had been injected daily with tritiated water throughout the gestation period. Feeding of the mice was maintained for 21 days. Results obtained for brain, lungs, heart, kidney, liver, spleen, small intestine, muscle, femur and testis after 21 days are given in Table 4.

Two closely related rat studies involving the ingestion of tritium in organic form have also been reported.[23,24] In both experiments groups of rats were fed OBT prepared in the same manner as by Golnik and Rochalska for five days. In one of the studies a second group was nourished with fodder containing only tritiated protein (TP) isolated from the OBT. The specific activity was measured for brain, lung, heart, kidney, liver, spleen, small intestine, muscle, femur, and skin (without hair). The results are compared with each other and the mice studies in Table 4.

Table 4: Relative tissue uptake in rodents

	MICE[a] OBT	RAT[b] TP	RAT[b] OBT	RAT[c] OBT	MICE[d] OBT	AVG
TESTIS	0.83				0.55	0.69 ± .14
MUSCLE	0.74	0.32	0.26	0.19	0.60	0.42 ± .07
SM. INT.	1.00	1.00	1.00	1.00	1.00	1.00
LIVER	1.20	1.16	1.06	0.87	0.92	1.04 ± 0.05
BRAIN	0.51	0.55	0.21	0.12	0.26	0.33 ± 0.07
LUNG		0.79	0.66	0.54	0.92	0.73 ± 0.06
HEART		0.55	0.21	0.39	0.49	0.41 ± 0.06
KIDNEY		0.53	0.77	0.58	0.84	0.68 ± 0.06
SPLEEN		0.63	0.94	0.59	0.83	0.75 ± 0.06
FEMUR		0.18	0.23	0.12	0.24	0.19 ± 0.02
SKIN		0.71	0.66	0.45		0.61 ± 0.08
FAT	0.62					0.62
TFWT	1.33					1.33

[a]Ref. 20

[b]Ref. 24

[c]Ref. 23

[d]Ref. 22

As can be seen from Table 4, while there is considerable overlap in the set of tissues investigated such overlap is not complete. Moreover, since different activities were used the data as presented were not directly comparable. In order to achieve concordance all results were calculated relative to the specific activity in the small intestine. The choice of this organ was arbitrary and based upon convenience. In addition the average relative uptake could then be calculated and this quantity along with an estimated uncertainty is listed in the table. In all but the first entry, standard deviations were used in the uncertainty estimate. This was not possible for testis since only two values were available so that the error estimate in this case was the range of the data. No uncertainty estimates could be made for fat or tissue free water.

The average relative uptake is shown in Figure 8. It is clear from the figure that the uptake is not uniform. OBT is found preferentially in liver and small intestine. A second important aspect is the evidence for a high degree of conversion provided by the large concentration in TFWT. This result is reassuring in that it indicates that assays based upon urine would be good indicators of the levels in the bulk of the tissues, while overestimating, but apparently never underestimating specific activities throughout.

6.2 DNA uptake

The issue of specific uptake of tritium in DNA following OBT exposure was investigated for mouse liver cells by Komatsu et al.[20] and for rat liver cells by Rochalska et al.[24]

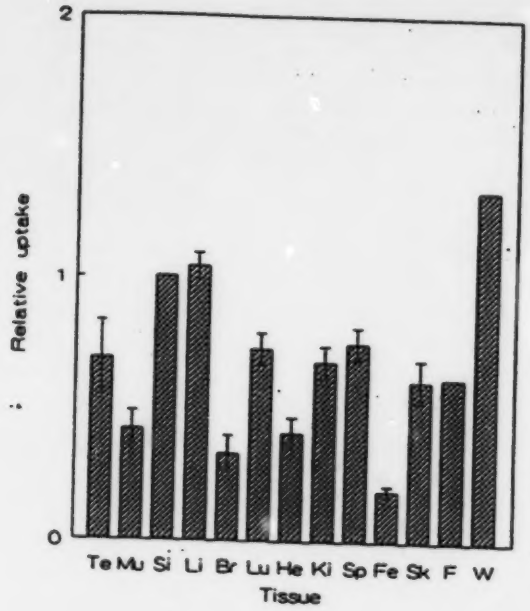

Figure 8: The relative uptake of organically bound tritium in rodents following long-term feeding of tritiated fodder. The graph shows the ratio of specific activity in testis (Te), muscle (Mu), liver (Li), brain (Br), lung (Lu), heart (He), kidney (ki), spleen (Sp), femur (Fe), skin (sk), fat (F), and tissue-free water (w) to that for small intestine (Si).

In the mouse study the authors found that the specific activity of DNA-bound tritium for OBT-fed animals was 4.6 times higher than for animals exposed to HTO. The authors state that the ratio of DNA-bound tritium specific activity to that for TFWT was 0.11 for HTO exposures. This would imply a ratio of about 0.5 for OBT intake.

For rat liver cells the difference between DNA-bound values for OBT and HTO exposures was more accentuated and the ratio of specific activities was found to be 13. After five days in which a 200 g rat was fed a total of 333 kBq (9 μCi) OBT the specific activity in liver DNA reached 6.4 $kBq \cdot g^{-1}$. Considering the total intake to be about 1.7 $kBq \cdot g^{-1}$ and that elimination has occurred this indicates a concentration factor of about four.

Following Saito et al.[17], the nucleus of a mouse liver cell has a mass of roughly 300 pg, and contains 12 pg of DNA. If one applies the DNA concentration of 4% implied by these figures to the nuclei of rat liver cells, then the nuclear activity concentration due to DNA-bound tritium would be only about .25 $kBq \cdot g^{-1}$. For rats the equivalent uniform (i.e. tissue-average) OBT specific activity in liver was measured to be 1.6 $kBq \cdot g^{-1}$. If an average figure of about 25% is used for the nucleoplasmic mass fraction then the equivalent value for DNA-bound tritium is .06 $kBq \cdot g^{-1}$. This result implies that 4% of the OBT becomes incorporated in DNA.

6.3 Retention times

Golnik and Rochalska[22] followed the time course of the OBT specific activity in each of the tissues studied. The measurements were performed for both wet and dry tissues and the results analyzed in terms of three component decays. The results are summarized in Table 5. As is well known, the determination of periods from multicomponent exponential decay data is difficult and a wide variation in individual results is observed. The authors do not give uncertainty estimates. By combining the results, 20 values for the periods of each of the three components are obtained. The average values are

$$T_1 = 1.2 \pm .2 \text{ days}$$
$$T_2 = 10 \pm 2 \text{ "}$$
$$T_3 = 65 \pm 8. \text{ "}$$

Table 5: The values of T_i parameters in wet and dry tissues of mice after 321 days contamination with OBT (from Ref. 21)

Tissue	Wet Tissue OBT			Dry Tissue OBT		
	T_1	T_2	T_3	T_1	T_2	T_3
Brain	1.7	18	154	1.3	35	35
Lungs	2.1	8	46	0.8	8	89
Heart	0.9	16	69	2.0	7	59
Kidneys	0.9	6	53	0.3	8	169
Liver	1.0	9	58	0.8	5	31
Spleen	0.7	5	38	0.9	8	36
Small intestine	0.7	4	43	0.5	9	69
Muscle	0.8	7	36	2.0	10	77
Femur	0.6	9	50	4.0	9	61
Testis	1.0	8	39	0.5	18	95

7. Conclusions

The quality factor corresponding to the electron degradation spectrum of tritium is 1.9 ± .2.

Estimates regarding the quality of tritium radiation are 1.6 ± .2 based upon an experimental study and 1.3 resulting from a simulation.

The average value of relative biological effectiveness of tritium based upon 55 individual estimates is 1.8 ± .1. The average values for in vivo and in vitro experiments exhibit no statistically significant difference. The average value for experiments with X-ray reference radiation is about 10% less than for those using γ-ray reference radiation.

Based upon the above, a reasonable estimate of the overall quality of tritium radiation is about 1.7.

These conclusions are summarized in table 6.

Table 6: Measures of Tritium Quality

Quality factor	1.9 ± .2
Specific energy	1.6 ± .2
Double strand breaks	1.3
RBE	1.8 ± .1
Average	1.7 ± .2

The average value of relative biological effectiveness for experiments involving the specific DNA precursor, tritiated thymidine, was significantly higher than for non-specific labelling by a factor of approximately 1.5. If correction for a possible confounding factor (temperature, see subsection 4.4) is made, the apparent difference vanishes. It is not possible to definitively rule out enhanced effects for DNA-incorporated tritium.

A relatively good estimate for the average localization factor for nuclear-bound tritium is four. A precise average for the localization factor of organically-bound tritium is not currently available but it is likely that it would not greatly exceed 1.5.

The specific activity of DNA-bound tritium following exposure to tritiated food is about 4% of that for organically-bound. This would imply an overall localization factor of 1.6. These conclusions are summarized in table 7.

Table 7: Localization Factors

DNA-bound	4.1 ± .2
Organically-bound	1.5 ± .2
Estimated overall	1.6 ± .2

Since in practice in vivo assessment will only provide information regarding the tissue average dose, for organically bound tritium an assessed dose of 1 Gy would imply a dose to all nuclei of 1.6 Gy. The relative effectiveness of the nuclear dose from tritium is on the average 1.7 times greater than the nuclear dose from reference X- or γ-radiation. Thus the critical quantity, the equivalent nuclear dose, is related to the tissue-average dose by the product of the localization factor with the quality. This implies that a suitable radiation weighting factor for organically-bound tritium is $w_R = 1.7 \times 1.6$ or approximately three. It is therefore concluded that current procedures may underestimate the equivalent dose by a factor of three for OBT.

The specific activity in rodents resulting from exposure to tritiated foodstuffs over periods of the order of weeks is not uniformly distributed over organs and tissues, but in all cases is less than that converted to tissue-free water.

The time course of organically-bound tritium in the organs of mice follows a three-component decay with average periods of 1.2 ± .2, 10 ± 2, and 65 ± 8 days.

8. Recommendations

(1) The principle of defining a separate radiation weighting factor for organically-bound tritium should be adopted.

(2) In the long term consideration should be given to establishing a value for w_R which as closely as possible reflects the potential radiotoxicology of organically-bound tritium. It is expected that this value would be somewhere between two and three.

(3) Extensive animal studies should be funded with the objective of determining localization factors as accurately as possible for a wide variety of tissues following feeding with tritiated fodder.

(4) An experimental investigation of the tritium dose-point kernel should be initiated.

(5) Radiobiological studies with the specific objective of investigating possible enhanced effects of incorporation should also be funded.

(6) The data base of relative biological effectiveness should be maintained.

9. References

1. Lederer, C. Michael and Shirley, Virginia S., Table of Isotopes (Seventh Edition) John Wiley & Sons Inc. N.Y. (1978)
2. ICRP Publication 38, Ann. ICRP (11-13) Pergamon Press, Oxford (1983)
3. Belot, Y., Rad. Prot. Dos., 16, 101 (1986).
4. Van den Hoek, J., Rad. Prot. Dos., 16, 117 (1986).
5. ICRP Publication 60, Ann. ICRP 21 (1-3) Pergamon Press, Oxford (1991).
6. NCRP Report No. 63 (1979).
7. Berger M.J. and Selzer S.M., National Bureau of Standards Report, NBSIR 82-2550-A (1982).
8. Barendsen, G.W., Curr. Top. in Rad. Res. Q. 4, 293 (1968).
9. Ellet W.H. and Braby L. A., Radiat. Res. 51, 229 (1972).
10. Kellerer, A.M. and Rossi, H.H., Radiat. Res. 47, 15 (1971).
11. Ito A., Monte Carlo Transport of Electrons and Photons. Plenum Press, N.Y. (1988).
12. Wolfe, Stephen L., In: Biology of the Cell. Second Edition. Wadsworth Publishing Co., Belmont California pp 245-246 (1981).
13. Ashley, J.C., Radiat. Res. 89, 25 (1982).
14. Prestwich W.V., Nunes J. and Kwok C., J. Nucl. Med. 30, 1036-1046 (1989).
15. Berger, M.J., National Bureau of Standards Report, NBSIR, 73 (1973).
16. Bedford, J.S., Rad. Res. 63, 531 (1975).
17. Saito M., Ishida M.R., Stuffer C. and Molls M., Health Phys. 48, 465 (1985).
18. Saito M., Ishida M.R. and Travis C.C., Health Phys. 56, 869 (1989).
19. Younis, A.R.S. and Watt, D.E., Phys. Med. Biol. 34, 821 (1989).
20. Komatsu K., Okumura Y. and Sakamoto K., Health Phys. 58, 625 (1990).
21. Swanson, J.A., Lee, M. and Knapp, P.E., J. Cell Biology 115, 941 (1991).
22. Golnik N and Rochalska M., Nukleonika 30 (1-2), 63 (1985).
23. Rochalska M., Szot Z., Zielczynski M., Nukleonika 24 (10-1), 1057 (1979).
24. Rochalska M., Szot Z., Nukleonika 24 (10-1), 1049 (1979).

BIBLIOGRAPHY

1956

Spalding JF, Lagham W and Anderson EC. 1956
The relative biological effectiveness of tritium beta-radiation with the broad bean root (Vicia faba) as a test system.
Rad. Res. 1956, 4:221.

1957

Furchner JE. 1957
Relative biological effectiveness of tritium beta-particle and Co^{60} gamma-rays measured by lethality in CF1 mice.
Rad. Res. 1957, 6:483.

Storer JB, Harris PS, Furchner JE and Langham WH. 1957
The relative biological effectiveness of various ionizing radiations in mammalian systems.
Rad. Res. 1957, 6:188-288.

1963

Wylie KF, Bigler WA, Grove GR. 1963
Biological half-life of tritium.
Health Phys. 1963, 9(9):911.

1965

Butler HL, Leroy JH. 1965
Observation of biological half-life of tritium.
Health Phys. 1965, 11(4):283.

Wylie KF, Bigler WA, Grove GR. 1965
Biological half-life of tritium.
Health Phys. 1965, 11(1):62.

1966

Berry RJ, Oliver R, Reiskin AB. 1966
Reproductive death of mammalian cells due to beta-radiation from incorporated thymidine labeled with H-3 or C-14.
Health Phys. 1966, 12(10):1461.

Bond VP, Feinendegen LE. 1966
Intranuclear H-3 thymidine:dosimetric, radiobiological & radiation protection aspects
Health Phys. 1966, 12(8):1007.

1967

Feinendegen LE. 1967
Tritium-labelled molecules in biology and medicine.
Academic Press, New York.

Hall EJ, Oliver R, and Bedford JS. 1967
The relative biological effectiveness of tritium beta particles compared to gamma radiation - its dependence on dose rate.
Br. J. Radiol. 1967, 40:704.

1969

Evans AG. 1969
New dose estimates from chronic tritium exposures.
Health Phys. 1969, 16(1):57.

Lambert BE. 1969
Cytological damage produced in the mouse testes by tritiated thymidine, tritiated water and x-rays.
Health Phys. 1969, 17:547.
Vennart J. 1969
Radio-toxicology of tritium and C-14 compounds.
Health Phys. 1969, 16(4):429.

1970
Judson GJ, Leng RA. 1970
The rate of synthesis and recycling of glucose in sheep determined with uniformly (14C)- and variously tritium-labelled glucose.
Proc. Aust. Biochem. Soc. 1970, 3:41. 14. Annual meeting of the Aust. Biochem. Soc., Parkville, Australia. 18 May 1970.
Moghissi AA, Lyon RJ. 1970
Tritium concentrations in food, 1967--1968.
Radiol. Health Data Rep. 1970, 11:233.
Pellerin P. 1970
Sources of tritium and its behavior upon release to the environment.
Health Phys. 1970, 19(4):586. By D.G. Jacobs. [Book Review]

1971
Kelly MJ, Booth RS. 1971
Quarterly progress report on radiological safety of peaceful uses of nuclear explosives: transfer of tritium to man from an initial wet deposition.
Oak Ridge National Lab., Tenn. (USA) 8 Jan 1971. 22 P.
Moghissi AA, Carter MW, Lieberman R. 1971
Long-term evaluation of the biological half-life of tritium.
Health Phys. 1971, 21(1):57.
Sadarangani SH, Sahasrabudhe SG, Soman SD, Moghissi SA (Ed.). 1973
Tritium excretion in man under tropical conditions. (Geographical variations in biological half-life of tritium in man.)
Las Vegas, NV. Messenger Graphics, Pub. 1973. P327-333. Tritium Symp. Las Vegas, Nevada, USA. 30 Aug 1971.

1972
Barth J, Stanley RE, Moghissi AA. 1972
Biological half-life of tritium in goats.
Health Phys. 1972, 22(4):396.
Ellet WH, Braby LA. 1972
The microdosimetry of 250 kVp and 65 kVp x-rays, ^{60}Co gamma rays, and tritium beta particles.
Rad. Res. 1972, 51:229.
McEwan AC. 1972
The critical organ for tritium gas.
Health Phys. 1972, 23(5):742.
Moghissi AA, Lieberman R. 1972
Comparison between tritium concentration in drinking water and body water.
Health Phys. 1972, 22(5):509.
Moghissi AA, Carter MW, Bretthauer EW. 1972
Further studies on the long-term evaluation of the biological half-life of tritium.
Health Phys. 1972, 23(6):805.

1973
Croach JW. 1973
Theoretical radiation dose to the human system from assimilated tritium.
Health Phys. 1973, 24(1):17.

1974
Balonov MI, Dolgirev EI, Likhtarev IA. 1974
Exchange kinetics and dosimetry of tritium oxide in man for different routes of administration.
Health Phys. 1974, 27(4):367.

1975
Bedford JS, Mitchell JB, Griggs HG and Bender MA. 1975
Cell killing by gamma rays and beta particles from tritiated water and incorporated tritiated thymidine.
Rad. Res. 1975, 63:531.
Burki H.J, Buner S, Ritter M and Cleaver JE. 1975
DNA damage from incorporated radioisotopes: influence of the ^{1}H location in the cell. Rad. Res. 1975, 62:299.
McMillan RC. 1975
Comments on "Exchange kinetics and dosimetry on tritium oxide in man for different routes of administration".
Health Phys. 1975, 28(6):826.
Nishizawa K, Takeuchi A, Hotta T. 1975
Examples of internal contamination by tritium-thymidine having short half-lives.
Health Phys. 1975, 29(2):348.
Ueno Y, Kawamura K. 1975
Study on the elimination of tritium in mice injected with tritiated water.
Health Phys. 1975, 29(3):413.

1976
Dobson RL, Kwan TC. 1976
The RBE of tritium radiation measured in mouse oocytes: increase at low exposure levels.
Rad. Res. 1976, 66:615.
Kasida Yosihiko, Arai Kiyohiko, Takeda Hirosi. 1976
Behavior of tritium in plants and animals. (In Japanese).
Nat. Inst. of Radiological Sciences, Chiba (Japan). p 78-80. 1st report on estimation of dose from exposure to natural and manmade radiation in the environment. Sep 1976.
Mullen AL, Moghissi AA, Stanley RE, Lloyd SR, Fort PA. 1976
Biological half-life of tritium in chickens and eggs.
Health Phys. 1976, 30(3):310.
Murphy CE Jr., Boni AL, Tucker SP. 1976
Conversion of gaseous molecular tritium to tritiated water in biological systems. (Role of soil microorganisms.)
Du Pont De Nemours (E.I.) & Co., Aiken, SC (USA). Savannah River Lab. Jun.1976 15 p

1978
Arai Kiyohiko, Takeda Hiroshi, Kasida Yoshihika. (Watanabe Hironobu, ed.) 1978
Tritium behavior in radio ecological food chain. (In Japanese).
Nat. Inst. Radiological Sciences, Chiba (Japan). p 81-91. Final report on the estimation of doses from exposure to natural and man-made radiation in the environment. Dec 1978.

Bovard P, Delmas J, Belot Y, Camus H, Grauby A, Kirchmann R, Hoek J Van Den. 1978
Transfer of tritium released by nuclear facilities to the food supply.
P. 419-431. Behaviour of tritium in the environment. Proc. Internat. Symp. jointly organized by the IAEA and the OECD Nuclear Energy Agency and held in San Francisco, 16-20 Oct. 1978. Vienna. IAEA. 1979. Proc. Series.

Lunec J, Cramp WA. 1978
The response of E.coli B^{s-1} to tritium β particles under aerated and anoxic conditions.
Int. J. Radiat. Biol. 1978, 34:537.

Pietrzak-Flis Z, Radwan I, Indeka L. 1978
Tritium in rabbits after ingestion of freeze-dried tritiated food and tritiated water.
Rad. Res. 1978, 76(2):420.

Rochalska M, Szot Z. 1978
Incorporation of organically bound tritium (obt) of food or tritium (obt) of food or tritiated water (tw) into foetuses, placentas and some tissues of pregnant rat.
Nukleonika. 1978, 23(10):1015.

1979

Clemente GF, Belloni P, Di Pietro S, Santori G, Santaroni GP. 1979
Tritium and plutonium content in the Italian diet and transfer to man.
IAEA, Vienna (Austria). 2:257-263. Biological implications of radionuclides released from nuclear industries. Proc. Internat. Symp. organized by IAEA, Vienna, 26-30 March 1979. Proc. series.

Nair S. 1979
A method for assessing the annual dose to the most exposed individual from tritium and 14C reactor discharges to atmosphere.
Central Electricity Generating Board, Berkeley (UK). Berkeley Nuclear Labs. Oct 1979. 67 P.

NCRP Report No. 62, 1979
Tritium in the environment.
NCRP 1979

NCRP Report No. 63, 1979
Tritium and other radionuclide labeled organic compounds incorporated in genetic material.
NCRP 1979

Osborne RV, Johnson JR. 1979
Problems in estimating effective dose equivalents from the results of bioassays for tritium.
Health Phys. 1979, 376:808.

Rochalska M, Szot Z. 1979
Tritium content in some organs and the DNA of rat-liver cells following short-term administration of tritiated food, tritiated protein or tritiated-water.
Nukleonika 1979, 24(10-1):1049.

Rochalska M, Szot Z, Zielczynski M. 1979
Radiation-dose absorbed in organs of rat after short-time feeding with organically bound tritium (Obt).
Nukleonika 1979, 24(10-1):1057.

Soldat JK, Baker DA. 1979
World-wide population doses from tritium released from nuclear facilities.
p. 575-582. Behaviour of tritium in the environment. Proc. Internat. Symp. jointly organized by IAEA and OECD Nuclear Energy Agency, San Francisco, 16-20 Oct. 1978. Vienna. IAEA. 1979. Proc. series.

Strack S, Kistner G, Emeis CC. 1979
Incorporation of tritium into planctonic algae in a continuous culture under dynamic conditions.
P. 219-230. Behaviour of tritium in the environment. Proc. of the Internat. Symp. jointly organized by IAEA and OECD Nuclear Energy Agency, San Francisco, 16-20 Oct. 1978. Vienna. IAEA. 1979. Proc. Series.
Willnow U. 1979
Effect of hyperthermia 42.5-degrees-C on the incorporation of 3H-thymidine into the DNA of solid tumors in childhood.
Archiv Fur Geschwulstforschung 1979, 49(5):429.

1980
Debouverie D, Binet J, Lejeune P, Vanvaerenbergh B. 1980
Radiotoxicity of tritium in water - lethal and mutagenic effects 3. Alterations of cytosine residues in Escherichia-coli DNA in culture-medium containing tritiated-water.
Archives Internat. de Physiologie et de Biochimie 1980, 88(4):B194.
Ito S, Fujita K, Teradaira R. 1980
Distribution and metabolism of tritium-labeled 5-s-cysteinyldopa in mice.
Biochem. Pharmacol. 1980, 29(24):3277.
Kirchmann R, Dupont JC, Egami Nobuo (ed.). 1980
Incorporation of tritium from various origins in freshwater fish and the radiological implication for man.
p. 39-43. Radiation effects on aquatic organisms. Tokyo. Japan Scientific Soc. Press. 1980. 306 P. Internat Symp. Zushi, Kanagawa, Japan. 11-12 May 1979.
Koenig LA 1980
Tritium uptake by plants.
P. 3-9. Status report on Radionuclide Transfer. Jan 1980. 166P. Report #INIS-MF-6902, Ministry of the Interior, Bonn, Germany.
Okada S, Nakamura N. 1980
RBE of tritiated-water for 3 radiobiological effects in cultured mammalian-cells.
J. Rad. Res. 1980, 21(1):44.
Rohwer PS, Etnier EL. 1980
Estimation of dose to man from environmental tritium.
Internat. J. Applied Rad. and Isotopes 1980, 31(8):460.
Tazima Y, Onimaru K. 1980
Mutagenic effectiveness of an internal gamma-emitter, tritium. 5. RBE of tritiated-water estimated by specific loci method in the silkworm.
J. Rad. Res. 1980, 21(1)45.
Vanvaerenbergh B, Binet J, Debouverie D, Lejeune P. 1980
Radiotoxic effects of tritium from tritiated-water - a study of laetal and mutagenic effects. 2. Measure of DNA-degradation on density gradients.
Archives Internat. Physiologie et de Biochemie 1980, 88(4)B210.
Vre RMD, Bertinchamps AJ, Grimeedeclerck R, Lejeune P. 1980
Radiobiological implications of restricted motion and isotope distribution in the hydration water layer of biological macro-molecules - a study by proton, deuterium and tritium nuclear magnetic-resonance spectroscopy.
Internat. J. of Rad. Biol. 1980, 38(1)120.
Willnow U. 1980
Comparative autoradiographic invitro study of the incorporation of 3H-thymidine and 3H-uridine into the DNA and RNA of solid tumors in children.
Archiv Fur Geschwulstforschung 1980, 50(8):778.

1981

Gerber GB, Maes J. 1981
Incorporation and turnover of tritium in neonatal mice & their mothers after feeding tritiated thymidine during pregnancy.
Health Phys. 1981, 40(5):755.

Glubrecht H, Kuehn W, Handl H, Bunnenberg C. 1981
Environmental exposure pathways and selected examples.
p. 258-273. Radioecology Symp. Proc. 1981. 628 p. Stuttgart (Germany, F.R.). 15-16 Oct 1981.

Hatch FT. 1981
Tritium and other radionuclide labeled organic compounds incorporated in genetic material.
Health Phys. 1981, 40(1):133. By NCRP [Book Review].

IAEA 1981
Tritium in some typical ecosystems. Final report of a five-year IAEA co-ordinated research programme on the environmental behaviour of tritium.
IAEA, Vienna (Austria). 124 P. Technical reports series. No. 207.

Ichimasa Y, Akita Y, Aoki R, Kato T, Tarumi H. 1981
Incorporation of tritium from HTO vapor into lipids and DNA of rat-tissues
J. Rad. Res. 1981, 22(1):66.

Kistner G, Kaul A (Ed.). 1981
Tritium contamination of environment and man.
P. 107-126. 20 years of radiation hygiene in the Federal Health Office. 1981. 159 P. Sth Berichte. No. 12. Scientific Colloquium: Federal Health Office. Neuherberg, Germany, F.R. 3 Apr 1981.

Komatsu Kenshi, Higuchi Masataka, Sakka Masatoshi. 1981
Accumulation of tritium in aquatic organisms through a food chain with three trophic levels.
J. Radiat. Res. 1981, 22(2):226.

Pietrzak-Flis Z, Radwan I, Major Z, Kowalska M. 1981
Tritium incorporation in rats chronically exposed to tritiated food or tritiated water for three successive generations.
J. Radiat. Res. 1981, 22(4):434.

Pietrzak-Flis Z. 1981
Effects of chronically ingested tritium on the oocytes of two generations of rats. (In German, English).
p. 17. Internat. Symp. on developmental disturbances after prenatal irradiation. Abstracts. 1981. 49 P. Neuherberg, Germany, F.R. 26-28 Nov 1980.

Radwan I. 1981
Influence of beta radiation from tritium and gamma radiation from 60Co on the biological half-times of organically bound tritium.
p. 208-213. Biological incorporation of tritium. Final report to the U.S. Environmental Protection Agency concerning Research Contract No. 05-536-3. 1981. 344 P.

Radwan I. 1981
Behavioral effects of chronic exposure to organically bound tritium and tritiated water. (In German, English).
Gesellschaft fuer Strahlen- und Umweltforschung M.B.H. Muenchen, Neuherberg (Germany, F.R.). Abt. Strahlenbiologie; Deutsche Roentgengesellschaft, gesellschaft fuer medizinische radiologie, strahlenbiologie und Nuklearmedizin E V, Hamburg (Germany,F.R.). p. 16. Internat. Symp. on Developmental Disturbances after Prenatal Irradiation. Abstracts. 1981. 49 P. Neuherberg, Germany, F.R. 26-28 Nov 1980.

Sadaie Y, Inoue T, Kada T, Mochizuki H. 1981
Efficiencies of DNA inactivation and mutation-induction by tritiated glycerol in bacterial systems.
J. Rad. Res. 1981, 22(4):387.

Till JE, Etnier EL, Meyer HR. 1981
Methodologies for calculating the radiation-dose to man from environmental releases of tritium.
Nuclear Safety 1981, 22(2):205.

Ueno AM, Furuno I, Matsudaira H. 1981
RBE of tritiated-water for cell killing, induction of micronuclei and mutation in dividing L5178Y-cells.
J. Rad. Res. 1981, 22(1):30.

1982

Commerford SL, Carsten AL, Cronkite EP. 1982
The turnover of tritium in cell-nuclei, chromatin, DNA, and histone.
Rad. Res. 1982, 92(3):521.

Commerford SL. 1982
The relative amount of organic and inorganic tritium present in the tissues of animals exposed to tritium through their drinking water or through their diet.
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):307.
Internat. Symp. on Radioecology. Wageningen (Netherlands). 28 - 30 Jun 1982.

Hoek J Van den, Gerber G, Kirchmann R. 1982
Tritium metabolism in cow's milk after administration of tritiated water and of organically bound tritium.
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):317. Internat. Symp. on Radioecology. Wageningen (Netherlands). 28-30 Jun 1982.

Ito A. 1982
Microdosimetry of the tritium beta-ray.
J. Rad. Res. 1982, 23(1):6.

Iwakura T, Takeda H. 1982
Computer-aided calculation to estimate dose contribution from successive tritium injection of organically bound form.
J. Rad. Res. 1982, 23(1):51.

Johnson JR. 1982
The estimation of the effective dose equivalent from tritiated water exposures using tritium concentrations in urine.
Rad. Prot. Dos. 1982, 2(4):245.

Kashida Yoshihiko, Arai Kiyohiko, Takeda Hiroshi, Nakane Ryohei, Isomura Shohei, Shimizu Masami (eds.). 1982
Food chain of tritium.
P. 257-269. Separation of deuterium and tritium. Tokyo (Japan). Gakkai Shuppan Senta. 20 Feb 1982. 315 P. Inst. of Physical and Chemical Research Symp. for Separation of Deuterium and Tritium. Wako, Saitama (Japan). 4 Dec 1980.

Kirchmann R, Fagnart E. 1982
Results of experimental research on the transfer of tritiated water to cultivated vegetables.
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):229.
Internat. Symp. on Radioecology. Wageningen (Netherlands). 28-30 Jun 1982.

Nuernberger E, Clausen E, Kistner G. 1982
Investigation on the distribution of tritium and carbon-14 in the amino acids of labelled green algae (Scenedesmus Quadricauda SSP.).
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):339.
Internat. Symp. on Radioecology. Wageningen (Netherlands). 28-30 Jun 1982.

Pietrzak-Flis Z, Radwan I. 1982
Effect of chronic ingestion of tritiated water and tritium organically bound in food on growth and reproductive functions of rats.
Nukleonika. 1982, 27(7-8):389.

Radwan I, Kriegel H, Schmahl W, Kistner G, Stieve FE. 1982
Behavioral effects of chronic exposure to organically bound tritium and tritiated water.
p. 105-110. Developmental effects of prenatal irradiation. Stuttgart (Germany, F.R.). G. Fischer. 1982. 387 P. Internat. Symp., Neuherberg (Germany, F.R.). 26-28 Nov 1980.

Rochalska M, Bruwaene R Van, Gerber GB, Kirchmann R. 1982
Organically bound tritium and its distribution in mice fed organically labelled milk powder.
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):345. Internat. Symp. on Radioecology. Wageningen (Netherlands). 28 - 30 Jun 1982.

Rochalska M, Hoek J Van Den, Kirchmann R, Gerber G, Bruwaene R Van. 1982
Incorporation of tritium in milk lipids after feeding organically bound tritium to cows.
Ann. Assoc. Belg. Radioprot. 1982, 7(3-4):331. Internat. Symp. Radioecology. Wageningen (Netherlands). 28-30 Jun 1982.

Sadaie Y, Inoue T, Kada T. 1982
DNA damages induced by beta-particles from tritiated-water.
J. Rad. Res. 1982, 23, (1):35.

Slatkin DN, Commerford SL. 1982
Statistical dosimetry of radiation to oocytes from DNA-bound tritium.
Health Phys. 1982, 42(1):77.

Strack S. 1982
Radiological studies on organically bound tritium. (In German).
KFT Nachr. 1982, 14(4):278.

Ueno AM, Furuno I, Matsudaira H. 1982
Effect of low dose-rate gamma-rays and tritiated-water on cultured mammalian-cells L5178Y. 2. Sensitization by deuterium-oxide.
J. Rad. Res. 1982, 23(1):46.

Ueno AM, Furunofukushi I, Matsudaira H. 1982
Induction of cell killing, micronuclei, and mutation to 6- thioguanine resistance after exposure to low-dose-rate gamma-rays and tritiated-water in cultured mammalian- cells (L5178Y).
Rad. Res. 1982, 91(3):447.

1983

Commerford SL, Carsten AL, Cronkite EP. 1983
The distribution of tritium among the amino-acids of proteins obtained from mice exposed to tritiated-water.
Rad. Res. 1983, 94,:151.

Etoh H, Hyodo-Taguchi Y. 1983
Effects of tritiated water on germ cells in medaka embryos.
Rad. Res. 1983, 93:332.

Feldt W, Kanisch G, Kanisch M, Lauer R. 1983
Radioecological studies in the Elbe River. Pt. 2. Plutonium, tritium. (In German). Sep 1983. 61 P. Berichte aus dem Isotopenlaboratorium der Bundesforschungsanstalt Fuer Fischerei Hamburg. No. 3.

Ikeda N. 1983
Long-lived radionuclides and assessment of environmental doses from them - tritium and C-14 - introduction - sources and distribution.
J. Rad. Res. 1983, 24(1):6.

Inomata Tsuyako. 1983
Behaviors of tritium in terrestrial biological system. (In Japanese).
P. 141-155. Proc. 9th National Inst. of Radiological Sciences Environmental Seminar on Study of Tritium Behavior in Environment and Human Body. 1983. 287 P. Chiba (Japan). 3-4 Dec 1981.

Kananishi N, Kinjo Y, Shiroya T, Watanabe M. 1983
Assay of tritiated-water-induced DNA lesion by alkaline elution.
J. Rad. Res. 1983, 24(1):51.

Komatsu Kenji. 1983
Behaviors of tritium in the aquatic biological system. (In Japanese).
P. 129-140. Proc. 9th National Inst. of Radiological Sciences Environmental Seminar on Study of Tritium Behavior in Environment and Human Body. 1983. 287 P. Chiba (Japan), 3-4 Dec 1981.

Myers DK, Gragtmans NJ, Johnson JR, Johnson LD, Jones AR, Osborne RV. 1983
RBE for induction of mammary-tumors in rats by tritium beta-rays.
Health Phys. 1983, 44(6):720.

Sadaie Y, Inoue T, Kada T, Mita I. 1983
Invitro analysis of the effect on DNA by tritiated-water.
J. Rad. Res. 1983, 24(1):67.

Saito M, Molls M, Streffer C. 1983
Tritium distribution in newborn mice after providing mother mice with drinking-water containing tritiated-thymidine.
Rad. Res. 1983, 95(2):273.

Takeda Hiroshi. 1983
Incorporation of organically bound tritium into body constituent molecules. (In Japanese).
National Inst. of Radiological Sciences, Chiba (Japan). p. 201-212. Proc. of the 9th National Inst. Of Radiological Sciences Environmental Seminar on Study of Tritium Behavior in Environment and Human Body. 1983. 287 P. Chiba (Japan). 3-4 Dec 1981.

Tisljarlentulis G, Commerford SL, Feinendegen LE, Henneberg P. 1983
The oxygen enhancement ratio for single-strand and double-strand breaks induced by tritium incorporated in DNA of cultured human t1-cells - impact of the transmutation effect.
Rad. Res. 1983, 94(1):41.

Ujeno Y. 1983
Relative biological effectiveness (RBE) of tritium beta-rays in relation to dose-rate Health Phys. 1983, 45(3):789.

Whicker FW. 1983
Radionuclide transport processes in terrestrial ecosystems.
Rad. Res. 1983, 94(1):135.

1984

Balonov MI, Kudritskaya OY. 1984
Mutagenic action of tritium upon the germ-cells of male-mice. 1. An induction of dominant lethal mutations by tritium oxide and the estimation of RBE
Genetika 1984, 20(2):224.

Balonov MI, Likhtarev IA, Moskalev YuI. 1984
The metabolism of H-3 compounds and limits for intakes by workers.
Health Phys. 1984, 47(5):761.

Commerford SL, Slatkin DN. 1984
Statistical dosimetry of radiation to oocytes from DNA-bound tritium - reply.
Health Phys. 1984, 46(4):957.

Cool DA, Maillie HD. 1984
Tritium distribution and excretion following intratracheal instillation of glass microballoon fragments in rats.
Health Phys. 1984, 46(3):599.

Crawford, Brown DJ. 1984
An age-dependent model of tritium metabolism following mixed (organic - inorganic) intakes.
Health Phys. 1984, 46(4):924.

Etnier EL, Travis CC, Hetrick DM. 1984
Metabolism of organically bound tritium in man.
Radiat. Res. 1984, 100(3):487.

Gragtmans NJ, Myers DK, Johnson JR, Jones AR, Johnson LD. 1984
Occurrence of mammary tumours in rats after exposure to tritium beta-rays and 200 kvp x-rays.
Rad. Res. 1984, 99(3):636.

Hoek J Van Den, Gerber GB, Kaul A, Neider R, Pensko J, Stieve FE, Brunner H (Eds.). 1984
Metabolism of ingested organically bound tritium in organic milk constituents and in tissues of two species of ruminants. p. 470-472. Radiation - risk - protection. Vol. 1. Compacts. Koeln (Germany, F.R.). Verl. Tuev Rheinland. 1984. 595 P. 6. Internat. Congress of the Internat. Radiation Prot. Assoc. (IRAP-6) and Exhibition. Berlin (Germany, F.R.). 7-12 May 1984.

Johnson JR. 1984
Statistical dosimetry of radiation to oocytes from DNA-bound tritium
Health Phys. 1984, 46(4):957.

Nakamura N, Okada S. 1984
Mutations and cell killing induced by tritium water in mouse lymphoma L5178Y-cells. 1. Acute exposure and RBE.
J. Rad. Res. 1984, 25:40.

Pietrzak-Flis Z, Radwan I. 1984
Dose estimation from chronic tritium exposure using tritium concentrations in urine and hair.
Health Phys. 1984, 46(2):460.

Pietrzak-Flis Z, Wasilewska Gomulka M. 1984
Effect of lifetime intake of organically bound tritium and tritiated water on the oocytes of rats.
Radiat. Environ. Biophys. 1984, 23(1):61.

Rancillac F, Pages P, Lochard J, Kaul A, Neider R, Pensko J, Stieve FE, Brunner H (Eds.). 1984
Radiological impact of tritium release from power plants. (In French).
P. 755-758. Radiation - risk - protection. V 2. Compacts. Koeln (Germany, F.R.). Verl. Tuev Rheinland. 1984. 424 P. 6. Internat. Congress of the Internat. Radiation Prot. Assoc. (IRAP-6) and Exhibition. Berlin (Germany, F.R.) 7-12 May 1984.

Spencer FS. 1984
Tritiated water uptake kinetics in tissue-free water and organically-bound fractions of tomato plants.
Ontario Hydro Research Lab., Toronto (Canada). Mar 1984. 32 P.

Tano S, Ueda S, Yamaguchi H. 1984
Effects of low-dose tritium labeled thymidine and uridine on the induction of somatic mutations in tradescantia.
Environmental And Experimental Botany 1984, 24(2):173.

Tazima Y, Onimaru K. 1984
Mutagenic effectiveness of tritiated-water on silkworm germ-cells - RBE obtained from sperm nuclei that fertilized tritiated oocytes.
J. Rad. Res. 1984, 25(1):36.

Teebor GW, Frenkel K, Goldstein MS. 1984
Ionizing-radiation and tritium transmutation both cause formation of 5-Hydroxymethyl- 2'-Deoxyuridine in cellular DNA. Proc. The National Academy of Sciences of the USA -Biological Sciences 1984, 81(2):318.

Travis CC. 1984
Metabolism of organically bound tritium.
Oak Ridge National Lab., Tn (USA). 1984. 22 P. US/Japan workshop on tritium radiobiology and health physics. Tokyo (Japan). 29 Oct-1 Nov 1984.

Yokoro K, Inoh A, Kinomura A, Nagao K, Seyama T, Yamamoto O, Yanagihara K. 1984
Patho-hematological changes observed in mice following administration of high-doses of tritiated-water (HTO).
J. Rad. Res. 1984, 25(1):36.

1985

Belovodskij LF, Gaevoj VK, Grishmanovskij VI. 1985
Artificial sources of tritium injection to the atmosphere and its behaviour in the environment.
P. 43-85. Tritium. (TRITIJ.) Moscow (USSR). Ejmergoatomizdat. 1985.

Etnier EL, Travis CC, Hetrick DM. 1985
Metabolism of organically bound tritium in man.
Rad. Res. 1984, 100(3):487.

Furuno-Fukushi I, Matsudaira H. 1985
Mutation induction by tritiated water and effects of deuterium oxide in cultured mouse leukemia cells.
Rad. Res. 1985, 103(3):466.

Geard CR. 1985
Chromosomal aberration production by 'track segment' charged particles as a function of linear energy transfer.
Rad. Prot. Dos. 1985, 13(1-4):199.

Golnik N, Rochalska M. 1985
Radiation doses absorbed in organs of mice fed with organically bound tritium (OBT) or tritiated water (TW).
Nukleonika. 1985, 30(1-2):63.

Hoek J Van Den, Gerber GB, Kirchmann R. 1985
Similarities and differences in the transfer of tritium and carbon-14 along the food chain. P. 361-362. Emergency planning and preparedness for nuclear facilities. Proc. of Internat. Symp. in Rome, 4-8 Nov. 1985. Vienna (Austria). IAEA. 1986. 581 P. Proc. series.

Kirchmann R, Gerber G, Fagniart E, Bruwaene R Van, Hoek J Van Den. 1985
Comparative studies on food chain pathways for tritium transfer to man following accidental exposure to tritium oxide. P. 345-348. Emergency planning and preparedness for nuclear facilities. Proc. Internat. Symp. in Rome, 4-8 Nov. 1985. Vienna (Austria). IAEA. 1986. 581 P. Proc. Series.

Kowalska M. 1985
Incorporation of tritiated water (HTO) or organically bound tritium (OBT) into amino acids of rat brain proteins.
J. Rad. Res. 1985, 26(1):99.

Kowalska M. 1985
Incorporation of tritiated water (HTO) and organically bound tritium (OBT) into phospholipids and gangliosides of rat brain.
J. Rad. Res. 1985, 26(4):385.

Liber HL, Little JB, Olaki VH. 1985
Toxicity and mutagenicity of low-dose rates of ionizing-radiation from tritiated-water in human-lymphoblastoid cells.
Mutation Res. 1985, 157(1):77.

Nakamura N, Morikawa N, Nogawa N, Okada S. 1985
The RBE of tritium beta-rays for mutagenesis in mouse lymphoma-cells under chronic irradiation conditions.
J. Rad. Res. 1985, 26(1):88.

Saito M, Ishida MR, Streffer C, Molls M. 1985
Estimation of absorbed dose in cell nuclei due to DNA-bound H-3.
Health Phys. 1985, 48(4):465.

1986

Belot Y, Caput C, Gauthier D. 1986
Distribution of the organically bound tritium in vegetation exposed to fall-out.

Rad. Prot. Dos. 1986, 16(1-2):111. Workshop on Environmental and Human Risks of Tritium. Karlsruhe (Germany, F.R.). 17-19 Feb 1986.

Blaylock BG, Hoffman FO, Frank ML 1986
Tritium in the aquatic environment.
Rad. Prot. Dos. 1986, 16(1-2):65. Workshop on environmental and human risks of tritium. Karlsruhe (Germany, F.R.). 17-19 Feb 1986.

Chen C-Z, Watt DE. 1986
Biophysical mechanism of radiation damage to mammalian cells by x-rays and gamma-rays.
Int. J. Rad. Biol. 1986, 49:131.

Hees M Van, Gerber GB, Kirchmann R, Vankerkom JH, Bruwaene R Van. 1986
Retention in young pigs of organically bound tritium given during pregnancy and lactation.
Rad. Prot. Dos. 1986, 16(1-2):123. Workshop on Environmental and Human Risks of Tritium. Karlsruhe (Germany, F.R.). 17-19 Feb 1986.

Ijiri K, Moukawa N, Shiroya T. 1986.
Cell death induced by tritiated water in mouse intestine studied in a new tritium safety clean cabinet.
Rad. Prot. Dos. 1986, 16(1-2):169.

Iwanami S, Oda N. 1986
Radiation quality of tritium beta-rays - microdosimetric distributions for nanometer-size targets in a medium containing tritiated-water.
Internat. J. Rad. Biol. 1986, 50(4):743.

Johnson JR, Myers DK, Gragtmans NJ. 1986
An experiment designed to measure the RBE of tritium for the induction of myeloid leukaemia in animals.
Rad. Prot. Dos. 1986, 16(1-2):161.

Kistner G. 1986
Uptake and distribution of tritium and carbon 14 via the food chains of man.
Bundesgesundheitsblatt. 1986, 29(3):89.

Kowalska-M. 1986
Incorporation of tritiated-water (HTO) and organically bound tritium (OBT) from food into 2 specific brain proteins.
Nukleonika 1986, 31(5-6):163.

Little JB. 1986
Induction of neoplastic transformation by low-dose-rate exposure to tritiated-water

Rad. Res. 1986, 107(2):225.

Matsudaira H. 1986
Effect of tritium in mammals.
Rad. Prot. Dos. 1986, 16(1-2):173.

Matsudaira H, Ueno AM, Furuno-Fukushi I, Yamaguchi T. 1986
Induction of cell killing, mutation and oncogenic transformation following exposure to tritiated water in cultured mammalian cells.
Rad. Prot. Dos. 1986, 16(1-2):145.

Muller WU, Streffer C, Molls M, Gluck L. 1986
Radiotoxicity of 3H-thymidine and 3H-arginine in pre-implantation mouse embryos in vitro.
Rad. Prot. Dos. 1986, 16(1-2):155.

Murphy CE Jr. 1986
Modeling tritium transport in the environment.
Du Pont de Nemours (E.I.) and Co., Aiken, SC (USA). Savannah River Lab. 1986. 28 P.
Workshop on environmental and human risks of tritium. Karlsruhe (Germany, F.R.). 17-19 Feb 1986.

Okada S, Sakai K, Nakamura N. 1986
Relative biological effectiveness of tritiated water on cultured mammalian cells at molecular & cellular level.
Rad. Prot. Dos. 1986, 16(1-2):137.

Rodgers DW. 1986
Tritium·dynamics in juvenile rainbow trout, salmo gairdneri.
Health Phys. 1986, 1:89.

Saito M, Ishida MR. 1986
Tritium metabolism in newborn mice and estimation of the accumulated dose.
J. Rad. Res. 1986, 27(1):50.

Saito M, Ishida MR. 1986
Tritium metabolism in newborn mice and estimation of the accumulated dose.
Rad. Prot. Dos. 1986, 16(1-2):131.

Smith H. 1986
Transformation and conversion of tritium in mammals.
Rad. Prot. Dos. 1986, 16(1-2):135.

Smith H. 1986
Round table discussion.
Rad. Prot. Dos. 1986, 16(1-2):189.

Spencer FS, Dunstall TG. 1986
Molecular tritium conversion in vegetation, litter and soil.
Rad. Prot. Dos. 1986, 16(1-2):89.

Straffer C. 1986
Effects of tritium on the molecular and cellular level.
Rad. Prot. Dos. 1986, 16(1-2):159.

Takakura K, Ishikawa M, Yasuda H. 1986
Single-strand breaks in DNA induced by tritiated-water at low-dose rate.
J. Rad. Res. 1986, 27(1):47.

Tano S. 1986
Effects of low dose tritiated water and tritium labeled compounds on the induction of somatic mutations in tradescantia.
Rad. Prot. Dos. 1986, 16(1-2):141.

van den Hoek J. 1986
Tritium metabolism in animals.
Rad. Prot. Dos. 1986, 16(1-2):117.

Van Hees M, Gerber GB, Kirchmann R, Vankerkom JH, Van Bruwaene R. 1986
Retention in young pigs of organically bound tritium given during pregnancy and lactation.
Rad. Prot. Dos. 1986, 16(1-2):123.

Yamada T, Matsuda Y, Ohyama H, Takiuchi H, Okuyama K. 1986
RBE of HTO radiation measured by its effects on cultured mouse embryos at pre-implantation stage.
Rad. Prot. Dos. 1986, 16(1-2):151.

1987

Brearley I. 1987
A dynamic model of the transfer of tritium through foodchains: sensitivity of dose predictions to variations in key parameters.
P. 337-345. Fusion reactor safety. Report of a technical committee meeting, Culham, 3-7 Nov. 1986. Dec 1987. 367 P.

Iwanami S, Oda N. 1987
Simple theory for the estimation of the mean absorbed dose in a cell in tritiated-water.
Phys. Med. and Biol. 1987, 32(12):1639.

Iwanami S, Oda N. 1987
Theory of relative biological effectiveness (RBE) of tritium beta-rays - bacteria killing effects of tritiated-water.
Phys. Med. and Biol. 1987, 32(11):1469.

Moghissi AA, Bretthauer EW, Patzer RG. 1987
Biological concentration of H-3.
Health Phys. 1987, 53(4):385.

Saito M, Ishida MR. 1987
Tritium metabolism in mice and a model for dose estimation.
J. Rad. Res. 1987, 28(1):8.

Saito Masahiro. 1987
Tritium behavior in the environment and in the mammalian body.
Annu. Rep. Research Reactor Inst., Kyoto Univ. Dec 1987, 20:98.

Sawada S, Enomoto T, Ono M. 1987
RBE values of Cf-252 fission neutrons and tritiated-water for neoplastic transformation of BALB/C 3T3 cells.
J. Rad. Res. 1987, 28(1):52.

Saito Masahiro, Ishida M R, Honda Yoshihide, Katsurayama Kousuke, Tsujimoto Tadashi (Eds.). 1987
A proposed model for the transfer of environmental tritium to man and tritium metabolism in model animals. (In Japanese).
P. 7-15. Proc. of the Short-Term Conference on Biological Transformation of Radionuclides in the Environment and Dose Assessment. Jun 1987. 76 P.
Kyoto Univ., Kumatori, Osaka (Japan). Research Reactor Inst.

1988

Brown RM. 1988
Assessment of the significance of organically-bound tritium in environmental materials.
Atomic Energy Control Board, Ottawa, On (Canada). Sep 1988. 35 p.

Ito A. 1988
Electron track simulation for microdosimetry.
Monte Carlo Transport of Electrons and Photons. Plenum Press, N.Y. 1988.

Rudran K. 1988
Significance of in vivo organic binding of tritium following intake of tritiated water.
Rad. Prot. Dos. 1988, 25(1):5.

Saigusa T. 1988
Distribution of LET-infinity of a tritium-beta particle.
J. Rad. Res. 1988, 29(1):62.
Saito M, Ishida MR. 1988
Metabolism of organically-bound tritium and a proposed model for dose estimation.
J. Rad. Res. 1988, 29(1):57.
Sakai K, Okada S, Suzuki N. 1988
Induction and repair of DNA breaks induced by tritium beta-rays in cultured mammalian-cells.
J. Rad. Res. 1988, 29(1):23.
Wirth E, Burkhardt J, Hinterstoisser C, Koehler H, Leising C, Lewis P, Regauer F. 1988
Mathematical, statistical analysis of the radiological calculation methods. Summary. Final Report (transfer factors). Schriftenreihe Reaktorsicherheit und Strahlenschutz - Ergebnisberichte, Untersuchungen, Studien, Gutachten. 1988. 32 p.

1989
Bryne BJ and Lee WR. 1989
Relative biological effectiveness of tritiated water to gamma radiation for germ line mutations.
Rad. Res. 1989, 117:469.
Gloebel B, Berlich J, Keller KD, Bauer U, Andres C, Zaeh I, Malter G, Fehrenz K, Lehnen H, Fehringer F. 1989
Determination and evaluation of the radiation dose to the population due to incorporation of natural radioactivity.
Schriftenreihe Reaktorsicherheit und Strahlenschutz. - Ergebnisberichte, Untersuchungen, Studien, Gutachten. Mar 1989. 234 p.
Hisamatsu S, Takizawa Y, Katsumata T, Itoh M, Ueno K, Sakanoue M. 1989
Further study on fallout 3H ingestion in Akita, Japan.
Health Phys. 1989, 57(4):565.
Hisamatsu, Shun-ichi, Takizawa, Yukio. 1989
Transfer of fallout tritium from environment to human body. (In Japanese)
Radioisotopes (Tokyo). 1989, 38(9):381.
Kistner G, Wirth E, (Leising C, Wirth E, (eds.)) 1989
Tritium in the pasture - cow - milk - pathway.
p. 101-115. Experiences with radiological assessment models, comparisons between predictions and observations. Proc. Jan 1989. 161 p. Workshop in radioecology. Neuherberg (Germany, F.R.). 5-7 Nov 1986.
Saito M, Ishida MR, Travis CC. 1989
Dose-modification factor for accumulated dose to cell nucleus due to protein-bound H-3.
Health Phys. 1989, 56(6):869.
Satow Y, Sawada S, Ohtaki M, Okada S, Nakamura N, Lee JY, Hori H. 1989
Effect of tritiated-water on female germ-cells - mouse oocyte killing and RBE.
Internat. J. Rad. Biol. 1989, 56(3):293.
Taylor DM. 1989
An approach to the proposal of an annual limit of intake for the general public (ALIGP) for organically bound tritium.
Rad. Prot. Dos. 1989, 28(3):211.
Wagner A. 1989
Radioecological investigations in the food-chain air-soil-vine-wine. Pt. 2. Final report. Schriftenreihe Reaktorsicherheit und strahlenschutz. - Ergebnisberichte, Untersuchungen, Studien, Gutachten. 208 P. Oct 1989.

Wirth E, Kaul A, (Grossklaus D. (ed.)). 1989
Radionuclide contamination of animal products.
p. 145-177. Residues in food derived from animals.
Parey. 1989. 183 p. Pareys Studientexte. no. 53. Berlin (Germany, F.R.).
Younis A-RS, Watt DE. 1989
The quality of ionising radiations emitted by radionuclides incorporated into mammalian cells.
Phys. Med. Biol. 1989, 34(7):821.

1990
Goldfinch EP. 1990
Erratum - Comment on the metabolism of H-3 and C-14 with special reference to radiation protection. [letter]
Rad. Prot. Dos. 1990, 32(3):203.
Johnson JR. 1990
Comment on the metabolism of H-3 and C-14 with special reference to radiation protection. [letter]
Rad. Prot. Dos. 1990, 32(2):131.
Kamiguchi Y, Tateno H, Mikamo K. 1990
Dose-response relationship for the induction of structural chromosome-aberrations in human spermatozoa after invitro exposure to tritium beta-rays.
Mutation Res. 1990, 228(2):125.
Komatsu K, Okumura Y, Sakamoto K. 1990
Radiation dose to mouse liver cells from ingestion of tritiated food or water.
Health Phys. 1990, 58(5):625.
Koenig LA. 1990
Tritium in the food chain.
Rad. Prot. Dos. 1990, 30(2):77. Radiation protection: a topical and steady task - seminar. Karlsruhe (Germany, F.R.). 23 Jun 1988.
Taylor DM, Moroni JP, Snihs JO, Richmond CR. 1990
The metabolism of H-3 and C-14 with special reference to radiation protection.
Rad. Prot. Dos. 1990, 30(2):87.
Yamamoto O, Ayaki H, Munesada K. 1990
Low-dose-rate effect of tritium beta-rays on transfection activity of phage DNA related to an oxidative species different from .OH, HO-2. O-2(-.), and H2O2.
Biochem. Internat. 1990, 20(5):903.

1991
Ellenbroek-FM, Cappenberg-TE. 1991
DNA-synthesis and tritiated-thymidine incorporation by heterotrophic fresh-water bacteria in continuous culture.
Applied and Environ. Microbiol. 1991, 57(6):1675.
Kim MA and Baumgartner F. 1991
Tritium fractionation in biological systems and in analytical procedures.
Radiochimica Acta 1991, 54:121.
Momoshima N, Okai T, Kaji T, Takashima Y. 1991
Distribution and transformation of various chemical forms of tritium in the environment.
Radiochimica Acta 1991, 54(3):129.
Papke H, Forstel H. 1991
Formation rate of nonexchangeable organically bound tritium from tritiated soil-water.
Health Phys. 1991, 60(6):773.

Takeda H. 1991
Incorporation and distribution of tritium in rats after chronic exposure to various tritiated compounds.
Internat. J. Rad. Biol. 1991, 59(3):843.
Wallmark B, Larsson H, Andersson K, Fryklund J, Helander HF. 1991
Tritiated-thymidine incorporation into DNA in rat gastric-mucosal cells.
Digestion 1990, 47(S1):39.

APPENDIX B

SLOWING DOWN THEORY

The spectrum of electrons emitted in beta decay is determined by the energy dependence of the nuclear transition probability. The spectral character of the radiation field resulting from the emission differs from the emission spectrum because the electrons become degraded in energy as they propagate through the medium. In general the spectrum is non-stationary, because it depends upon position with respect to the source. If the source is uniformly dispersed however, then at any point in the medium electrons will arrive at all stages of degradation. In this case a unique spectrum, referred to as the equilibrium spectrum results. The nature of the slowing-down process and the resultant spectrum are determined by the nature of electron transport.

Electron transport is governed by the Boltzmann equation. If integrated over all directions this may be written

$$\nabla \cdot J + \mu \cdot \phi = Y + \int \tilde{\mu}(E',E) \cdot \phi(E')dE' \qquad (B1)$$

In this equation $J(E,r)$ is the vectorial fluence spectrum while $\phi(E,r)$ is the fluence spectrum. Both are characterized by dimensions $cm^{-2} \cdot keV^{-1}$, and represent the value for electrons of energy E. The source density spectrum is $Y(E,r)$ and is described dimensionally in units of $cm^{-3} \cdot keV^{-1}$. Interaction between an electron with initial energy E_i and the medium leaving the electron with energy E_f is described by the differential interaction coefficient $\tilde{\mu}(E_i,E_f)$ which has units $cm^{-1} \cdot keV^{-1}$. The total interaction coefficient is obtained by integration to obtain

$$\mu(E_i) = \int \tilde{\mu}(E_i,E_f)dE_f \qquad (B2)$$

It is convenient to introduce the energy loss

$$w = E_i - E_f \qquad (B3)$$

and describe the interactions in terms of initial energy and energy loss.

In terms of these variables the transport equation may be written

$$\nabla \cdot J = Y + \int \tilde{\mu}(E+w,w)\phi(E+w)dw - \int \tilde{\mu}(E,w)\phi(E)dw \qquad (B4)$$

The first integral represents fluence from higher initial energy, $E_i = E + w$, which contributes to the fluence at general energy E. The second integral represents losses from the group at energy E, corresponding to interactions for which $E_i = E$.

The continuous slowing down approximation assumes that the interaction probability is significant only for the condition $w \ll E$. Taylor's expansion of the first integrand about E gives

$$\tilde{\mu}(E+w,w)\dot{\phi}(E+w) = \tilde{\mu}(E,w)\dot{\phi}(E) + \frac{d}{dE}[\tilde{\mu}(E,w)\dot{\phi}(E)]\cdot w \quad (B5)$$

In this approximation equation (B4) becomes

$$\nabla\cdot J = Y + \frac{d}{dE}\left\{\phi(E)\int \tilde{\mu}(E,w)\cdot w\cdot dw\right\} \quad (B6)$$

The integral in the above expression is equivalent to the product of the average energy loss with the probability of an interaction per unit path length. Since this corresponds to the rate of energy loss with distance it may be identified as the stopping power S(E). Thus in the continuous slowing down approximation the equation becomes

$$\nabla\cdot J = Y + \frac{d(S\phi)}{dE} \quad (B7)$$

For a uniform source distribution all field quantities must be independent of the spatial coordinate r and hence the first term vanishes. The solution for the equilibrium fluence spectrum is then

$$\phi(E) = S(E)^{-1}\cdot\int_E^{\infty} Y(E')dE' \quad (B8)$$

The equilibrium fluence spectrum calculated above corresponds to the radiation field resulting from the propagation of the primary particles. A complete solution to the transport equation is obtained without making the continuous slowing down approximation by solving instead the complete integral equation given by equation (B1) without the first term. An intermediate approximation leads to the Spencer-Fano equation [B1]. The solution to this equation may be obtained by iteration with the solution of equation (B8) forming the first iteration. The second iteration corresponds physically to including in the fluence distribution the first generation of secondary electrons or delta particles released by ionization impact from the primary fluence. These particles also slow down during the course of their transport.

The effective source density of δ-rays produced by the primary fluence, which extends to a maximum energy E_o, the endpoint energy of the beta-spectrum, is

$$Y_\delta(E) = \int_{2w}^{E_o} \tilde{\mu}(E',w)\phi(E')dE' \quad (B9)$$

where the energy loss of the primary electron, w, is related to the δ-ray energy, E, by

$$w = E + I \quad (B10)$$

In equation (B10) the quantity I represents the binding energy of the secondary electron and it is assumed that $I \ll E_o$. In this case I = 12.6 eV and E_o = 18.6 keV. Since both the primary electron and δ-ray are identical particles, the maximum energy loss is one-half of the incident energy. The δ-ray fluence spectrum is then given as

$$\phi_\delta(E) = S(E)^{-1} \cdot \int_E^{E_c/2} Y_\delta(E')dE' \qquad (B11)$$

In order to calculate the δ-ray effective source density in this work the description of the impact ionization interaction coefficient developed by Jain and Khare [B2] was used. This description is based upon the fact that at energy transfers large compared to the binding the interaction may be treated as free electron scattering, governed by the Moller interaction coefficient $\tilde{\mu}_M(E,\epsilon)$ where E is the incident energy of the primary particle and ϵ is the energy of the δ-ray. For soft collisions in which the process must be treated as an interaction with the entire atom, the appropriate cross section is the Born-Bethe interaction coefficient designated as $\tilde{\mu}_B(E,w)$, where $w = \epsilon + I$.

The complete interaction coefficient is taken as a weighted average

$$\tilde{\mu}(E,\epsilon) = f_1(E,\epsilon)\cdot\tilde{\mu}_B(E,w) + f_2(E,\epsilon)\cdot\tilde{\mu}_M(E,\epsilon) \qquad (B12)$$

The weighting factors, f_1 and f_2, are such that the cross section varies smoothly from the Born-Bethe value at low energies to the Moller value at high energies. In order to evaluate the Born-Bethe interaction coefficient, the continuum oscillator strength function must be determined. This was estimated for water from the photoabsorption cross section [B3] in the energy range from the ionization threshold, 12.6 eV, to the limit of the measurements at 60 eV. For purposes of computation the data were represented by an appropriate gamma function. Above 60 eV an exponential representation suggested by Jain and Khare [B2] was used. It should be noted that the photoabsorption data were obtained for H_2O vapour and alterations to the strength function for the condensed state must be expected.

Following ionization in which a K-shell vacancy is created, deexcitation leads to emission of an Auger electron at 0.49 keV. The production density of Auger electrons is given by

$$Y_A = \int \mu_K(E)\cdot\phi(E)dE \qquad (B13)$$

In the above integral the first term is the interaction coefficient for K-shell ionization. The corresponding microscopic cross section is approximated by

$$\sigma_K(E) = \frac{2\pi b e^4}{E\cdot E_K}\cdot\ln(c\cdot E/E_K) \qquad (B14)$$

where E_K is the K-shell binding energy, and b and c are constants chosen to best fit the experimental data [B4].

The calculation was achieved using a Fortran code specially written by us for this project. The stopping power was taken from Ashley [B5]. The emission and primary electron fluence spectra were calculated on a 1000-point grid. This led to a 500-point grid for the δ-ray fluence spectrum.

Appendix References

[B1] Spencer L.V. and Fano U., Phys. Rev. 93, 1172 (1954).
[B2] Jain D.K. and Khare S.P., J. Phys. B. 9, 1429 (1976).
[B3] Cairns R.B., Harrison H. and Schoen R.I., J. Chem. Phys. 55, 4886 (1971).
[B4] Powell C.J., Rev. Mod. Phys. 48, 33-47 (1976).
[B5] Ashley J.C., Radiat. Res. 89, 25 (1982).

RBE DATABASE

REFERENCE	Bedford J.S. Rad.Res. 63 531-543 (1975)	
ENDPOINT	Survival	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	3HTdR	REF RAD 60 Co
METHOD	Frozen, unifilar label, in vitro	
RBE	4.4	

REFERENCE	Bedford J.S. Rad.Res. 63 531-543 (1975)	
ENDPOINT	Cell Survival	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	3HTdR	REF RAD 60 Co
METHOD	Frozen bifilar	
RBE	4.4	

REFERENCE	Bedford J.S. Rad.Res. 63,531-543 (1975)	
ENDPOINT	Cell survival	
ORGANISM	Chinese hamster	CELL LINE V79B
COMPOUND	3HTdR	REF RAD 60 Co
METHOD	Frozen unifilar label	
RBE	3.0	

REFERENCE	Bedford J.S. Rad.Res. 63,531-543 (1975)	
ENDPOINT	Cell survival	
ORGANISM	Chinese hamster	CELL LINE V79B
COMPOUND	3HTdR	REF RAD 60 Co
METHOD	Frozen bifilar	
RBE	3.0	

REFERENCE	Bedford J.S. Rad.Res. 63,531-543 (1975)	
ENDPOINT	Cell survival	
ORGANISM	Chinese hamster	CELL LINE V79B
COMPOUND	3HTdR	REF RAD 60 Co
METHOD	3HTdR unifilar	
RBE	1.8	

REFERENCE	Bedford J.S. Rad.Res. 63,531-543 (1975)	
ENDPOINT	Cell survival	
ORGANISM	Chinese hamster	CELL LINE V79B
COMPOUND	HTO	REF RAD 60 Co
METHOD	Tritiated water	
RBE	1.8	

REFERENCE	Byrne,B.J. and W.R.Lee Rad.Res.117,469,1989	
ENDPOINT	mutation	
ORGANISM	Drosophila	CELL LINE
COMPOUND	HTO	REF RAD 60 Co
METHOD	Tritiated water in food	
RBE	2.7	

REFERENCE	Dewey W.D.,Humphrey R.M. and Jones B.A. Rad.Res.24(1965)	
ENDPOINT	Chromosome aberrations	
ORGANISM	Hamster	CELL LINE B14
COMPOUND	3HTdR	REF RAD 60Co
METHOD	Dose for 2 visible aberrations	
RBE	0.7	

REFERENCE	Dewey W.D.,Humphrey R.M. and Jones B.A. Rad.Res.24(1965)	
ENDPOINT	Chromosome aberrations	
ORGANISM	Hamster	CELL LINE B14
COMPOUND	HTO	REF RAD 60Co
METHOD	Dose for 2 visible aberrations	
RBE	1.2	

REFERENCE	Dobson R.L. and Kwan T.C. Rad.Res. 66, 615-625(1976)	
ENDPOINT	Oocyte Cell survival	
ORGANISM	Mouse	CELL LINE
COMPOUND	HTO	REF RAD 60 Co
METHOD	Intraperitoneal injection and feeding of mothers. RBE dose dependent	
RBE	3.0	

REFERENCE	Etoh,H. and Y.Hyodo-Taguchi Rad.Res. 93,332 (1983)	
ENDPOINT	Male germ cell survival	
ORGANISM	Oryzias latipes	CELL LINE
COMPOUND	HTO	REF RAD 137Cs
METHOD	Medaka exposed continuously to HTO. Germ cell survival in fry scored	
RBE	1.8	

REFERENCE	Etoh,H. and Y.Hyodo-Taguchi Rad.Res. 93,332 (1983)	
ENDPOINT	Female germ cell survival	
ORGANISM	Oryzias latipes	CELL LINE
COMPOUND	HTO	REF RAD Cs137
METHOD	Medaka exposed continuously to HTO. Germ cell survival in fry scored	
RBE	2.2	

REFERENCE	Furchner J.E. Rad.Res.6,483,1957	
ENDPOINT	% mortality in 30 d	
ORGANISM	CF1 mice	CELL LINE
COMPOUND	HTO	REF RAD 60Co
METHOD	Single IP injection. Groups of 20 animals each receiving a set dose.	
RBE	1.7	

REFERENCE	Furuno-Fukushi,I. and H.Matsudaira Rad.Res. 103,466 (1985)	
ENDPOINT	6TG resistance	
ORGANISM	Mouse (leukemia)	CELL LINE L5178Y
COMPOUND	HTO	REF RAD gamma
METHOD	HTO at dose rates 0.025 to 0.15 Gy/hr, for 20 hours. RBE for mutation frequency of 5×10^{-5}.	
RBE	2.5	

REFERENCE	Furuno-Fukushi,I. and H.Matsudaira Rad.Res. 103,466 (1985)	
ENDPOINT	Cell survival	
ORGANISM	Mouse (leukemia)	CELL LINE L5178Y
COMPOUND	HTO	REF RAD gamma
METHOD		
RBE	2.0	

REFERENCE	Gragtmans,N.J. et al Rad.Res. 99,636 (1984)
ENDPOINT	Mammary tumours
ORGANISM	Sprague-Dawley rat CELL LINE
COMPOUND	HTO REF RAD 200 kVp X-rays
METHOD	Intraperitoneal injection
RBE	1.2

REFERENCE	Hall E.J. et al Br.J.Radiol. 40, 704 (1967)
ENDPOINT	Cell population growth
ORGANISM	Human CELL LINE HeLa
COMPOUND	HTO REF RAD 60Co or radium
METHOD	Monolayer culture of HeLa S3 cells, growth curves determined. Dose rate 0.5 to 3 rad/hr.
RBE	2.0

REFERENCE	Hall E.J. et al Br.J.Radiol. 40, 704 (1967)
ENDPOINT	cell survival
ORGANISM	Human CELL LINE HeLA
COMPOUND	HTO REF RAD 60Co or radium
METHOD	Monolayer culture of HeLa S3 cells, growth curves determined. Dose rate: 32 rad/hr.
RBE	1.0

REFERENCE	Hall E.J. et al Br.J.Radiol. 40, 704 (1967)
ENDPOINT	inhibition primary root growth
ORGANISM	Vicia seedlings CELL LINE
COMPOUND	HTO REF RAD 60Co or radium
METHOD	Seedlings grown in tank of HTO. After irr. kept 10 d at 19 degrees. Dose rate 1.52 rad/hr.
RBE	1.6

REFERENCE	Hall E.J. et al Br.J.Radiol. 40, 704 (1967)
ENDPOINT	inhibition primary root growth
ORGANISM	Vicia seedlings CELL LINE
COMPOUND	HTO REF RAD 60Co radium
METHOD	Seedlings grown in tank of HTO After irr. kept 10 d at 19 degrees. Dose rate 46.3 rad/hr.
RBE	1.0

REFERENCE	Ijiri,K. et al Rad.Prot.Dos 16(1-2):169 (1986)
ENDPOINT	Ilium epithelial cell survival
ORGANISM	mouse CELL LINE
COMPOUND	HTO REF RAD 137 Cs
METHOD	HTO 2Ci/ml;0.2 ml injected IP. 50 crypt sections/mouse scored.
RBE	1.6

REFERENCE	Kamaguchi,Y. et al Mutation Res. 228(2),125 (1990)
ENDPOINT	Chromosome abnormalities (4)
ORGANISM	Human [spermatozoa] CELL LINE
COMPOUND	HTO REF RAD X-ray
METHOD	Semen samples in B.W.W. medium with 1.53-24.3 mCi/ml for 80m. Samples placed in insemination medium with zona-free hamster oocytes. Dmin.
RBE	2.4

REFERENCE	Kamaguchi,Y. et al Mutation Res. 228(2),125 (1990)	
ENDPOINT	Chromosome abnormalities (4)	
ORGANISM	human germ cells	CELL LINE [Spermatozoa]
COMPOUND	HTO	REF RAD X-ray
METHOD	Semen samples in B.W.W. medium with 1.53-24.3 mCi/ml for 80m Dmax.	
RBE	1.4	

REFERENCE	Lambert,B.E. Hlth.Phys.17,547(1969)	
ENDPOINT	Sperm cell survival	
ORGANISM	DBA2 mouse testes	CELL LINE
COMPOUND	3HTdR	REF RAD 250 kVp X-rays
METHOD	IP injections, 0.5 to 40 uCi/g body mass. Death of intermediate and type B spermatogonia monitored.	
RBE	1.3	

REFERENCE	Lambert,B.E. Hlth.Phys.17,547(1969)	
ENDPOINT	Sperm cell survival	
ORGANISM	DBA2 mouse testes	CELL LINE
COMPOUND	HTO	REF RAD 250 kVp X-rays
METHOD	IP injections	
RBE	2.4	

REFERENCE	Lunec,J. and W.A.Cramp Int.J.Rad.Biol. 34(6),537 (1978)	
ENDPOINT	Cell survival	
ORGANISM	Bacterium E.coli	CELL LINE B/s-1
COMPOUND	HTO	REF RAD 7 MeV electrons
METHOD	Cell grown to late log phase in glucose-supplemented medium.	
RBE	1.2	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
ENDPOINT	Cell survival (50%)	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	HTO	REF RAD gamma
METHOD	Cell culture exposed to 20-180 MBq/ml, for 20 hours.	
RBE	2.0	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
ENDPOINT	mutation frequency of 5e-5	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	HTO	REF RAD gamma
METHOD	Cell culture exposed to 20-180 MBq/ml, for 20 hours.	
RBE	2.5	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
ENDPOINT	cell survival of 50%	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	amino acids	REF RAD gamma
METHOD	Cell culture exposed [50 hours]	
RBE	2.0	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
ENDPOINT	mutation frequency of 5e-5	
ORGANISM	Mouse	CELL LINE L5178Y
COMPOUND	amino acids	REF RAD gamma
METHOD	Cell culture exposed [50 hours]	
RBE	2.5	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
ENDPOINT	oncogenic transformation	
ORGANISM	Mouse	CELL LINE confluent 10T1/2 cells
COMPOUND	HTO	REF RAD gamma
METHOD	Cell culture exposed to HTO for 20h	
RBE	1.6	

REFERENCE	Matsudaira,H. et al Rad.Prot.Dos. 16,145 (1986)	
END POINT	Oncogenic transformation	
ORGANISM	Mouse	CELL LINE confluent 10T1/2 cells
COMPOUND	HTO	REF RAD gamma
METHOD	Cell culture exposed to HTO for 20h	
RBE	1.6	

REFERENCE	Moskalev, Y.I. et al, 240, Tritium (1973)	
ENDPOINT	LD50/4	
ORGANISM	Rat	CXLL LINE
COMPOUND	HTO	REF RAD 137Cs
METHOD		
RBE	2.0	

REFERENCE	Moskalev, Y.I. et al, 240, Tritium (1973)	
ENDPOINT	LD50/12	
ORGANISM	Rat	CELL LINE
COMPOUND	HTO	REF RAD 137 Cs
METHOD		
RBE	1.4	

REFERENCE	Moskalev, Y.I. et al, 240 Tritium (1973)	
ENDPOINT	LD50/30	
ORGANISM	Rat	CELL LINE
COMPOUND	HTO	REF RAD 137Cs
METHOD		
RBE	1.3	

REFERENCE	Moskalev, Y.I. et al, 240, Tritium (1973)	
ENDPOINT	Leukocyte survival	
ORGANISM	Rat	CELL LINE
COMPOUND	HTO	REF RAD 137Cs
METHOD		
RBE	1.9	

REFERENCE	Moskalev, Y.I. et al, 240, Tritium (1973)	
ENDPOINT	Lymphocye survival	
ORGANISM	Rat	
COMPOUND	HTO	REF RAD 137Cs
METHOD		
RBE	1.5	

REFERENCE Moskalev, Y.I. et al, 240, Tritium (1973)
ENDPOINT Thymic weight response
ORGANISM Rat CELL LINE
COMPOUND HTO REF RAD 137Cs
METHOD
RBE 1.9

REFERENCE Moskalev, Y.I. et al, 240, Tritium (1973)
ENDPOINT Spleenic weight response/3d
ORGANISM Rat CELL LINE
COMPOUND HTO REF RAD 137Cs
METHOD
RBE 1.7

REFERENCE Moskalev, Y.I. et al, 240, Tritium (1973)
ENDPOINT Spleenic weight response/7d
ORGANISM Rat CELL LINE
COMPOUND HTO REF RAD 137Cs
METHOD
RBE 1.9

REFERENCE Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT Cell survival
ORGANISM Mouse CELL LINE L5178Y
COMPOUND HTO REF RAD Cs137
METHOD Acute exposure to concentrated solution 1-4 Gy
RBE 1.0

REFERENCE Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT mutation-6TG resistance
ORGANISM Mouse CELL LINE L5178Y
COMPOUND HTO REF RAD Cs137
METHOD Acute exposure to concentrated solution 1-4 Gy
RBE 1.3

REFERENCE Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT mutation-MTX resistance
ORGANISM Mouse CELL LINE L5178Y
COMPOUND HTO REF RAD Cs137
METHOD Acute exposure to concentrated solution 1-4 Gy
RBE 1.2

REFERENCE Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT DNA scissions
ORGANISM Mouse CELL LINE L5178Y
COMPOUND HTO REF RAD Cs137
METHOD Acute exposure to concentrated solution 1-4 Gy
RBE 0.6

REFERENCE Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT Inhibition of DNA replication
ORGANISM Mouse CELL LINE L5178Y
COMPOUND HTO REF RAD Cs137
METHOD Acute exposure to concentrated solution 1-4 Gy initiation measured.
RBE 1.0

REFERENCE	Okada,S. et al Rad.Prot.Dos. 16(1-2):137-140 (1986)
ENDPOINT	Inhibition of DNA replication
ORGANISM	Mouse CELL LINE L5178Y
COMPOUND	HTO REF RAD Cs137
METHOD	Acute exposure to concentrated solution 1-4 Gy continuation measured.
RBE	1.8

REFERENCE	Satow,Y. et al Int.J.Radiat.Biol.56(3),293 (1989)
ENDPOINT	Oocyte cell survival
ORGANISM	ICR strain mice CELL LINE
COMPOUND	HTO REF RAD 137 Cs
METHOD	MBq/g HTO injected in abdominal cavities of 14 d mice.
RBE	1.1

REFERENCE	Satow,Y. et al Int.J.Radiat.Biol.56(3),293 (1989)
ENDPOINT	Oocyte cell survival
ORGANISM	ICR strain mice CELL LINE
COMPOUND	HTO REF RAD 137Cs
METHOD	MBq/g HTO injected in abdominal cavities of 14 d mice.
RBE	3.5

REFERENCE	Spalding J.F. et al Rad.Res.4,221 (1956)
ENDPOINT	LD50 for root growth
ORGANISM	Vicia faba
COMPOUND	HTO REF RAD 175 kVp X-rays
METHOD	LD50 determined for cessation of root growth for 4 consecutive days
RBE 1.0	

REFERENCE	Storer J.B. et al Rad.Res.6,188 (1957)
ENDPOINT	Spleni weight loss
ORGANISM	Mouse, CF1 females
COMPOUND	HTO RAD REF radium
METHOD	Single IP injection; tritiated water to keep level. Score after 5 d.
RBE 1.3	

REFERENCE	Storer J.B. et al Rad.Res.6,188 (1957)
ENDPOINT	thymic weight loss
ORGANISM	Mouse, CF1 females
COMPOUND	HTO REF RAD radium
METHOD	Single IP injection; tritiated water to keep level. Score after 5 d.
RBE 1.5	

REFERENCE	Storer J.B. et al Rad.Res.6,188 (1957)
ENDPOINT	59Fe uptake in red blood cells
ORGANISM	Sprague-Dawlet rat (male)
COMPOUND	HTO REF RAD 60Co
METHOD	59Fe injected 2d after HTO IP injection. Same as mice otherwise.
RBE	1.6

REFERENCE	Warters,R.L. et al Curr.Top. Radiat. Res. 12,389 (1977)
ENDPOINT	Survival
ORGANISM	Chinese hamster
COMPOUND	3HTdR REF RAD 250 kVp X-rays
METHOD	In vitro study on ovary cells
RBE	0.9

REFERENCE	Yamada J. et al Rad.Prot.Dos. 16(1-2):151 (1986)
ENDPOINT	Blastocyst formation rate
ORGANISM	Mouse pre-implantation embryos CELL LINE
COMPOUND	HTO REF RAD 60Co
METHOD	In vitro fertilization BC3F1f+ICRm mice. Fertilized eggs grown in culture
RBE	1.5

REFERENCE	Yamada J. et al Rad Prot Dos. 16(1-2):151 (1986)
ENDPOINT	Chromosome aberrations (at first cleavage metaphase)
ORGANISM	Mouse pre-implantation embryos CELL LINE
COMPOUND	HTO REF RAD 60 Co
METHOD	In vitro fertilization BC3F1f+ICRm mice. Fertilized eggs grown in culture
RBE	1.5